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RIVER ICE JAMS

A LITERATURE REVIEW

by

S. J. Bolsenga

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DESCRIPTORS: river ice jam formation, growth, decay; ice jam effects on water levels and bed configuration; forecasting ice jams; ice breaking; dusting; thermal regime modification; surface and aerial explosives in combatting ice jams; ice retention and diversion structures; surging; channel modification.

Great Lakes Research Center
U. S. Lake Survey

June 1968

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FOREWORD

This report presents the results of a literature search on ice jam characteristics and methods of prevention and removal. The investigation was sponsored by the Rock Island District, Corps of Engineers as the initial step in a comprehensive study of river ice problems.

The program was conducted under the direction of Dr. L. Bajorunas, Director, Great Lakes Research Center. Foreign language manuscripts were translated by M. Stefaniuk, W. P. Ward, and S. J. Bolsenga Sr. The manuscript was proofread by M. Stefaniuk. The assistance of all is gratefully acknowledged.

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SUMMARY

Published information on river ice jams in many areas of the world was collected, examined, and summarized during this investigation. All manuscripts were collected and examined without regard to their apparent pertinence. The result provides a summarization of both current and historical information on the ice jam mechanism and methods of prevention and removal.

Descriptions of ice jam characteristics range from mathematical to narrative treatments. Methods of prevention and removal range from dusting and thermal pollution to the more widely used blasting. Trends in the use of these techniques are indicated.

The lack of success in applying prevention and removal techniques seems to be due to lack of basic information on ice jam characteristics. The results of this report can be useful in that field since a guideline for future research planning is provided.

RIVER ICE JAMS

A LITERATURE REVIEW

BY

S. J. BOLSENGA

GREAT LAKES RESEARCH CENTER
LAKE SURVEY DISTRICT, CORPS OF ENGINEERS
DETROIT, MICHIGAN

INTRODUCTION

The purpose of this report is to present summaries of published papers containing information on river ice jam characteristics, and the methods of prevention and removal. About 400 manuscripts are reviewed. The only similar study was by Bydin and Kopylova (1932) in which 22 manuscripts were examined.

Literature was acquired from several sources. The initial manuscript list was compiled from the Bibliography on Snow, Ice and Permafrost (U. S. Army Cold Regions Research & Engineering Laboratory, 1951-66). After acquisition, the manuscript reference lists were examined for additional items. Personal communication with investigators in ice jam research provided several preprint manuscripts and locally published papers.

Foreign language manuscript translations were by staff members, local university faculty, and qualified private parties. All titles were submitted to several translation depositories to avoid duplicate translation. The Office of Science Information Service of the National Science Foundation provided advice on translation methods.

All manuscripts were acquired regardless of author, publication date, or apparent pertinence. In summarizing the manuscripts direct quotations are used. Controversial papers are included and opposing papers are usually grouped. However, unpublished opinions are not recorded.

In report summaries, many parts of the original manuscripts are omitted both for brevity and to eliminate unnecessary material. Some reports are divided into more than one chapter of this report to group related information.

ICE JAM CHARACTERISTICS & EFFECTS

General Characteristics

The fact that considerable disagreement exists among investigators of ice jam characteristics is illustrated effectively by interpretations of the definition of an ice jam. Piotrovich (1954) defines an ice jam as "a piling up of ice debris in a river section during spring or autumn ice drifting, producing closure of the channel and sharp fluctuations of water levels." According to the Glossary of Meteorology (American Meteorological Society, 1959) an ice jam is "an accumulation of broken river ice caught in a narrow channel, frequently producing local floods during a spring breakup." The Functional Glossary of Ice Terminology (U. S. Navy Hydrographic Office, 1952) describes an ice jam as "an accumulation of broken river ice caught in a narrow channel." Deslauriers (1965) defines an ice jam simply as "an accumulation of ice debris."

Triquet (1965) defines and classifies several types of river ice during the periods of formation, growth and decay. During the growth stage, when autumn ice jams can occur, the following formations are defined:

"Ice bridge: the ice blocks, carried on the flowing surface, become arrested upon the shores at certain narrow spots on the river.... Other blocks become hung-up on those there and the section of flow becomes greatly restricted in area, impeding the passage of following ice blocks: the surface of the section becomes completely blocked forming a bridge upon which other ice blocks become juxtaposed."

"Hanging dam: the addition under an ice field of flocks of frazil....

"Ice jam of capture: produced when, because of hydraulic conditions of the flow, ice blocks are thrown violently under the leading edge of the field instead of being juxtaposed there...."

During the decay stage, when spring ice jams can occur, Triquet (1965) defines some additional types of ice jams.

"Spring ice jam: halt and accumulation of drift ice, at a narrowing or obstacle....

"Static ice jam: a case of a spring ice jam where the drift ice has taken a stable position and does not completely block the flow section....

"Dynamic ice jam: the case of a spring ice jam in evolution where the drift ice accumulates until it completely blocks the flow section...."

Problems in understanding ice jams are perhaps due to a lack of basic data. Deslauriers (1965) offers a possible explanation. "Break-up phenomena are hazardous and violent; that probably explains why physical laws and characteristics of same are amongst the least known of all ice phenomena in rivers."

Reports in this section should have application to river ice jams in most locations of the world. However, nearly every investigation is based on local data. Therefore, care should be exercised when using constants in the equations. They must be changed and theories modified to suit the local situation.

Formation, growth & decay mechanism

The importance of investigation on the mechanism of ice jams is stated by Bezuglov (1959): "The problem of combatting ice jams and the floods provoked by them is extremely crucial, however, adaptation of rational measures for overcoming the jam phenomena is rendered difficult because of insufficient investigation of the responsible mechanism, and the lack of actually tested methods."

Popov (1957) lists some causes for ice jam occurrence and some difficulties in ice jam studies. "The main difficulty in the study of ice jam formations is the complexity of organizing observations in connection with the numerous causes upon which the phenomena depend, including purely local causes. Nevertheless, a careful study of even the sporadic materials of observations on ice jams in various rivers elucidate a number of conditions, furthering the formation of ice jams and determining the greater or smaller rise of water level.

"All these conditions can be divided into two catergories: local or morphological conditions associated with the character of river bed, its valley, slope and plane contours; and hydrometeorological conditions associated with the thickness of ice and its melting, the development of inundation in a river, the sequence of ice breakup, current speeds, etc.

"As demonstrated by experience, the formation of ice jams occurs in such places as steep bends of rivers, shallow sectors, island areas and where the longitudinal slope decreases abruptly.... The effect of all the mentioned factors of jam formation is associated with decrease in the transporting ability of a river, owing to which a temporary stoppage in the flow of ice and its accumulation occurs in such places.

"The size of ice jams, their potency and the support for water level caused by them are determined by a number of hydrometeorological conditions, the most important of which are: 1) the formation of immobile ice below the section of a river where the breakup of ice occurs, 2) great thickness and firmness of ice at the moment of breakup, 3) a sufficiently great intensity in the rise of water level, causing a breakup of a large river sector when the ice is very firm."

"The ice jam is destroyed by the action of the traction force of the stream when it exceeds the resistance force that holds the ice accumulation. Therefore, the larger the ice accumulation, the higher rise of water level is necessary in order to remove the ice jam that has been formed. The stability of ice jam is furthered to a considerable degree also by weather conditions. If, for instance, cooling sets in at the moment of ice breakup in a river, the firmness of the ice jam increases and the water level needed for its destruction must be increased. It has also been observed that the formation of potent ice jams during the ice breakup in rivers is furthered by conditions of the stoppage of ice flow, notably in the case of the large autumn jams.

"The main factors determining the height of water level maximum during ice jams are as follows: 1) the character of river bed and valley in the sector where the jam occurs, 2) the thickness of ice cover and its firmness, 3) the intensity of influx of flood water (intensity of rise in water level) and the ice movement connected with it, 4) the height of water level in the sector below the jam and 5) weather conditions during the formation of the ice jam. The rise of water level as a result of ice jam at a definite point in the river will also depend upon the distance of the point from the place where the jamming occurs.

"The above-mentioned most important conditions determining the formation of ice jams and the height of rise in water level, of course, do not exhaust all of the possible causes. But even this listing shows how great their scope is and how difficult it is to express them numerically, in order to enable us to determine with a sufficient accuracy the place of ice jam formations and the water level maximum during the jam."

It is equally important to know the evolution of river ice since autumn ice jams are influenced by the formation process and spring ice jams by the growth and decay processes. An analysis of river ice processes alone is an extensive subject and not within the scope of this report. Nevertheless, the following two papers are offered as background information.

Michel (1966) analyzes the formation, growth and decay mechanism of river ice covers.

"Basic processes of ice cover progression in rivers

"Two basic processes contribute to the covering up with ice of rivers: The first one might be called the frazil ice evolution process which starts with the supercooling of water and the production of frazil crystals, the latter gradually developing into ice flocks and floes finally forming a continuous ice cover. The second one might be called the border ice growth process which may be further subdivided into border ice growth by thermal exchanges only and border ice extension by frazil flocks. Border ice growth starts in areas of laminar flow along the banks: ice is nucleated starting right in contact with the colder material of the bank and this nucleation will propagate on the surface towards the middle of the flow, forming a clear and solid ice sheet. That type of growth may be further extended by frazil flocks which, because of their spongy nature, have a great tendency to cling to the irregular structure of border ice edges.

"Frazil ice evolution process

"Let us examine (Michel, 1965) the evolution of water temperature along the axis of a section of river submitted to below 0° C air temperature (fig. 3). Considering uniform flow, an initial water temperature above 0° C and also a constant rate of heat transfer per unit of surface over the section, a given volume of water will be submitted to a rate of cooling until it is supercooled to a point where frazil crystals will start to appear. Since in turbulent flow water molecules intermix, the water temperature and consequently the crystallization process takes place in depth over the whole cross-section of the flow.

"At the moment when the rate of cooling starts to decrease, ice crystals begin to grow and there is a production of frazil ice until water temperature comes back up to 0° C at a rate which gradually decreases. During that time individual crystals agglomerate to form vaporous flocks whose volume depend on the degree of turbulence of the flow. Once the water temperature is back to 0° C, there is no more appreciable production of individual frazil particles. The flocks have a very high porosity and consequently a density not much different from the density of water; they oscillate in the turbulent flow and more ice is formed in the interstices as they reach the surface. Those who reach the surface and stay there long enough start the formation of ice floes: water imprisoned between crystals freezes at the surface, and more continuous ice pieces are developed. As water-air temperature exchange keeps on going, the ice floes gradually get thicker and larger. If the flow is less turbulent, the concentration of flocks at the surface is greater and ice floes are more rapidly formed. Where the process can last over long distances, floes of important size will be developed (fig. 4). In long stretches of very turbulent flow, only a very compact type of slush will be formed.

"Criterium for the progression of ice covers

"Much analytical and experimental work has been done on the mechanical condition of progression of an ice cover fed by frazil ice flocks and ice floes. The worst hydraulic conditions limiting the progression of an ice cover has been called the criterium for the progression of the cover.

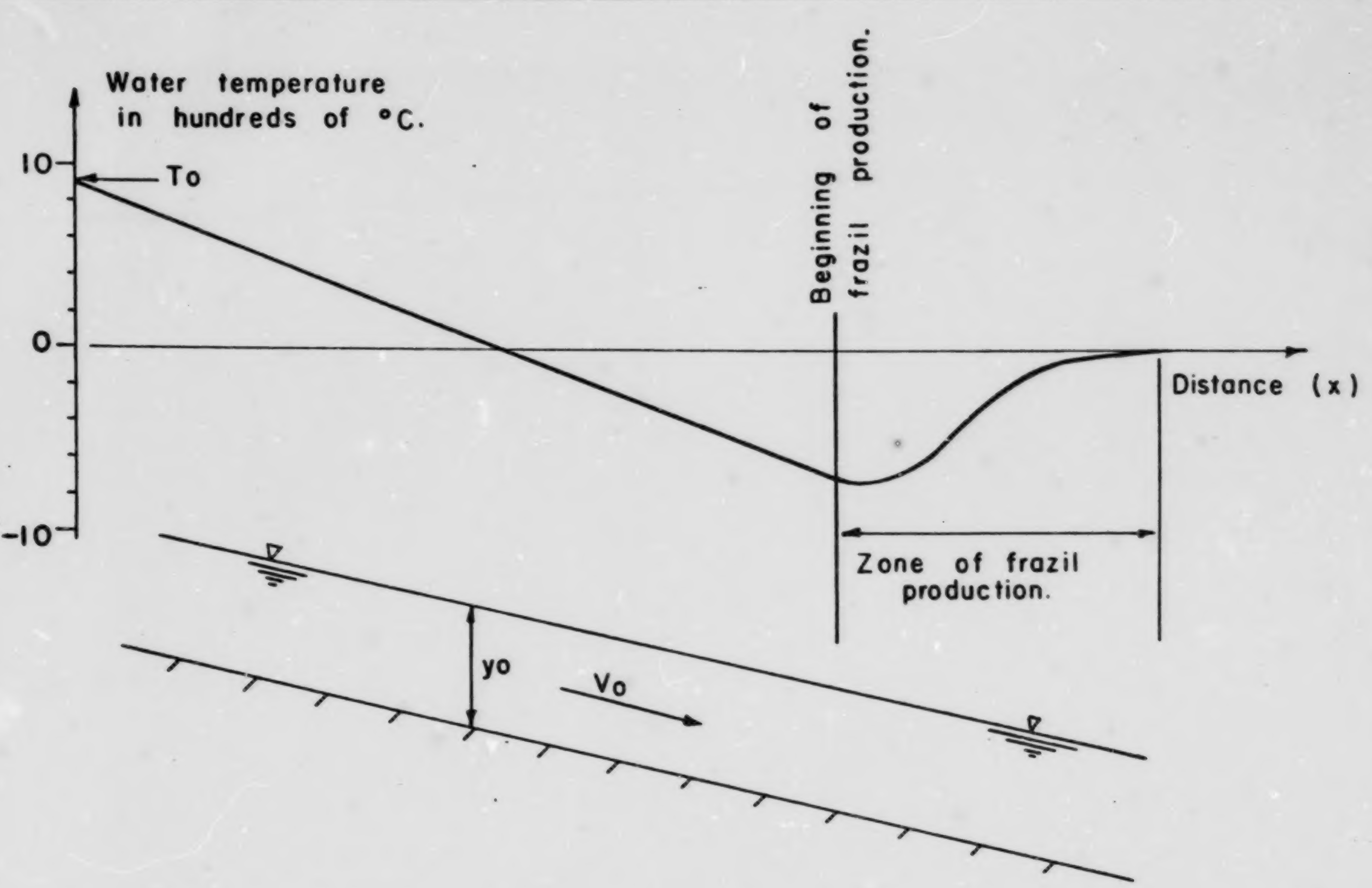

Water temperature
in hundreds of °C.
10
0
-10
To
Beginning of frazil production.
Distance (x)
Zone of frazil production.
yo
Vo

FIG. 3 - EVOLUTION OF WATER TEMPERATURE ALONG THE AXIS OF A SECTION IN UNIFORM FLOW. (Michel, 1966)

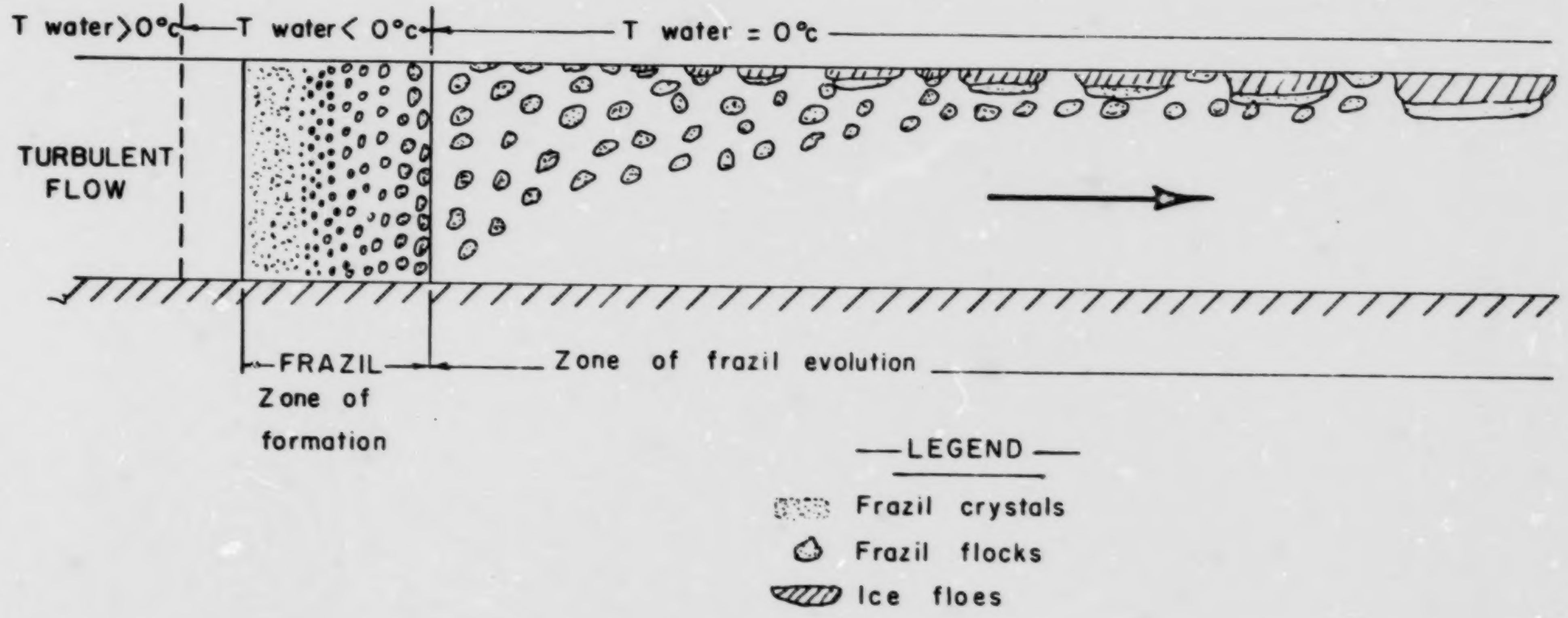

T water > 0°c
T water < 0°c
T water = 0°c
TURBULENT FLOW
FRAZIL Zone of formation
Zone of frazil evolution
—LEGEND—
Frazil crystals
Frazil flocks
Ice floes

FIG.4 — FRAZIL EVOLUTION IN RIVERS. (Michel, 1966)

"The first publication on hydrodynamic conditions controlling the progression of ice covers was written by McLachlan in 1927. From observations made on ice cover movements on the St-Lawrence River, he concludes: 'A very regular ice cover is formed in rivers at water velocities not exceeding 1.25 feet per second, when the temperature is at 0° F and there is no strong wind. Ice covers may thicken and progress at velocities up to 2.25 feet per second without floes passing underneath.'

"Those observations were later confirmed in a more detailed and precise way by Cousineau, after many years of observations on the St-Lawrence. He concludes that the 2.25 feet per second velocity is, in fact, an upper limit which can be reached only under ideal conditions of ice cover progression.

"Results of many years of observation of ice cover progression in the northern rivers of the U.S.S.R. are condensed in a book written by Estifeev and published in 1958, where he says: 'Frazil coming up to surface to develop into ice floes cannot form an ice cover at velocities higher than 2.3 to 2.6 feet per second.'

"Kivisild in 1959 declares that the Froude number of the flow in front of an ice cover is a valid criterium to determine whether the cover will progress upstream or floes will pass underneath it. From measurements made in many rivers, he concludes that the limiting value for the Froude number is around 0.08.

"In 1959 (sic) also, Cartier relates that it was impossible to obtain upstream progression of an ice cover feeded with big ice floes at velocities higher than 2.3 feet per second, from experiments made in a canal 9 feet in depth and 46 feet in width. (See Cartier, 1960 in a subsequent paper.)

"In 1961, Pariset and Hausser, present a complete theoretical analysis of the mechanics of the formation and stability of ice covers in rivers. They find that for narrow rivers the Froude number is also a valid criterium for the condition of progression of the cover. For wide rivers they develop a new criterium using the equilibrium conditions of an ice accumulation under the effect of the tangential forces.

"In 1965, (Michel, 1966) we find theoretically that the Kivisild criterium is valid for the mechanical progression of an ice cover. The relation of equilibrium of the upstream edge of the cover can be formulated as follows:

$$F_r = \frac{V}{\sqrt{gy}} = \sqrt{2 \frac{(\rho-\rho^1)}{\rho} (1-\varepsilon) \frac{t}{y}} \quad (1 - \frac{t}{y})$$

where:

F_r = Froude number of the flow in front of the upstream edge
V = Velocity in feet per second in front of the upstream edge
y_1 = Depth of water in feet, in front of the upstream edge
ρ, ρ^1 = Specific masses of water and solid ice
ϵ = Porosity of the accumulation
t = Thickness of the upstream edge in feet, when in equilibrium

From the preceding formula the maximum value for F_r can be obtained directly by derivation:

$$F_r = 0.154 \sqrt{(1 - \epsilon)}\text{."}$$

"Kivisild's results are most useful in attempting to give limiting values to the Froude number. Those results come from measurements made at the beginning of the winter on many rivers. Measurements made on Beauharnois Canal during four consecutive winters are also useful for the same purpose (fig. 5). In the case of the Beauharnois measurements, the two upper points correspond to the feeding of the cover with big ice floes, and the two lower points to feeding with very thin sheets of ice and ice slush.

"In spite of the lack or precision of the above datum we see that the Kivisild criterium corresponds to ice floes of porosity 0.73 for ideal conditions of progression, and frazil flocks of porosity 0.90 corresponds to difficult conditions of progression. Those values are on the security side both ways: with them we can calculate the limiting values of the velocity, which are given in the following table:

DEPTH IN FEET	APPROXIMATE VALUE OF LIMITING VELOCITIES FOR THE PROGRESSION OF AN ICE COVER IN FEET/SEC.	
	(Kivisild's Ideal conditions)	(Difficult conditions)
40	2.9	1.8
30	2.5	1.5
20	2.0	1.3
10	1.4	0.9
5	1.0	0.6

"It can be seen that taking into account the porosity gives a scale of values consistent with the main group of observations made in nature.

"An ice cover may progress simply by juxtaposition if the floes feeding it are large enough. The stability of the ice block itself is

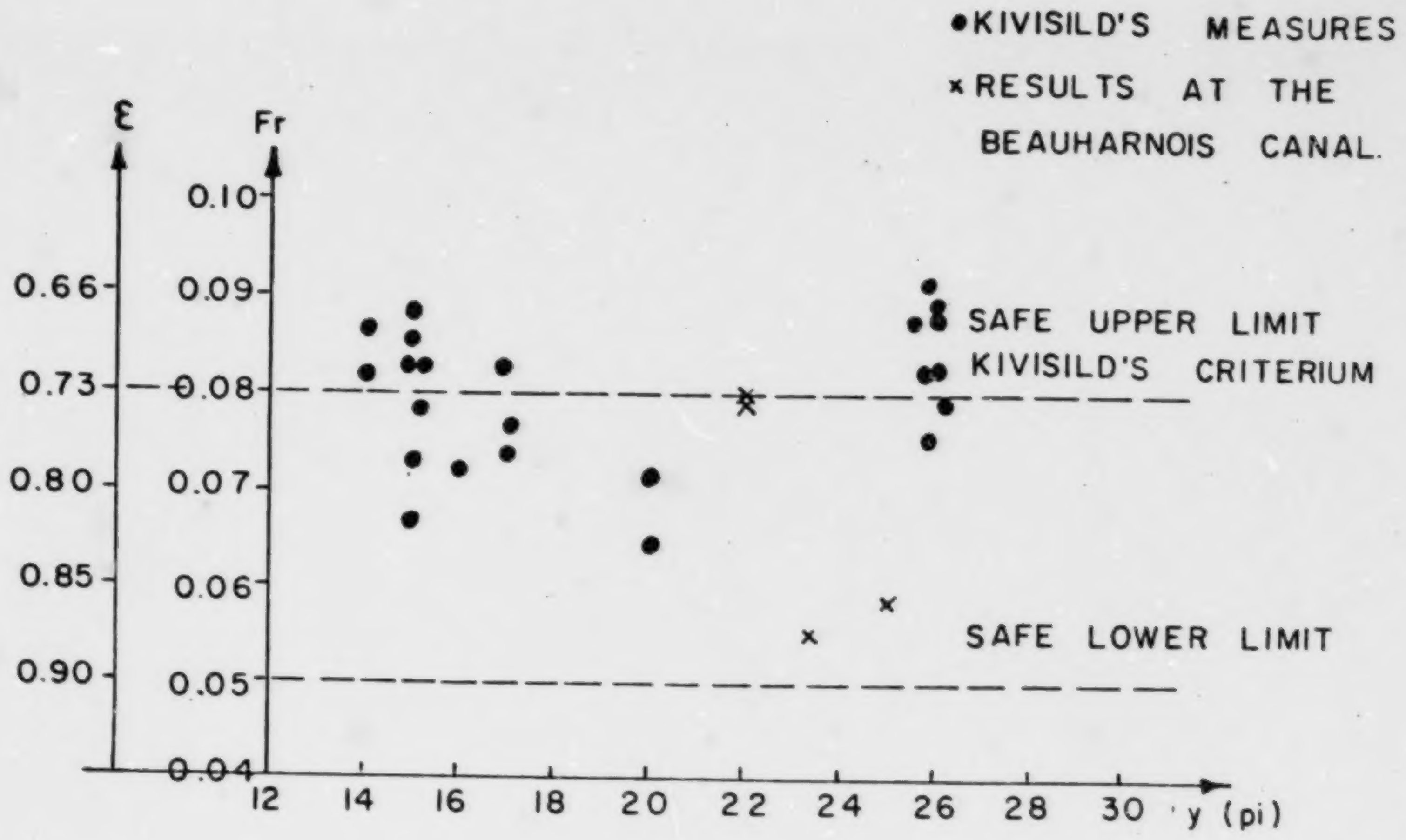


FIG.5 - EQUILIBRIUM LIMITS FOR AN ICE COVER DURING ITS FORMATION. (Michel, 1966)

given by (Michel, 1957):

$$V_s < K\sqrt{2g\ \frac{(\rho-\rho^1)}{\rho}\ d}$$

where:

V_s = mean velocity under the block
d = thickness of the block
K = form coefficient (around 1.3 for flat blocks)

"Formation of underhanging dams

"When the upstream (Michel, 1965) edge of an ice cover has reached a section of river where the velocity is such that it cannot progress further upstream, such as at the foot of rapids, floes and frazil are forced to pass underneath the cover and are carried downstream until the velocity of the flow becomes low enough for them to deposit on the underside of the cover. They accumulate and narrow the flow section until the velocity gets high enough to carry them further downstream (fig. 6)."

"The border ice growth process

"Border ice (Michel and Triquet, 1966) is the first type ice to appear in a river in areas of laminar flow along the banks. Because in laminar flow there is no intermixing of the top layer with the bottom layers, the temperature differences are important either in the vertical direction or in the horizontal one away from the banks. The top layer adjacent to the bank will go through undercooling considerably while the average temperature of water in the middle of the river will still be much above freezing point. Ice will be nucleated starting right in contact with the colder (because more conductive) material of the banks and this nucleation will propagate on the surface towards the middle of the flow, forming a clear and solid ice sheet.

"The edge of this ice sheet will finally come in contact with the turbulent water and its further progress will depend only on the thermal atmospheric exchange as compared to the temperature and turbulence of the water. By no means will the growth process be stopped only because the water is warmer than freezing point.

"Let us consider, fig. 7, the case where the edge of the border ice is parallel to the direction of the flow. There will be a velocity gradient in a direction x normal to the edge along the top surface layer. The velocity will be zero at the boundary and will attain a reference value outside the boundary layers.

"Very close to the edge there will be a laminar sublayer followed by the turbulent layer. Because of the Reynolds similitude of heat

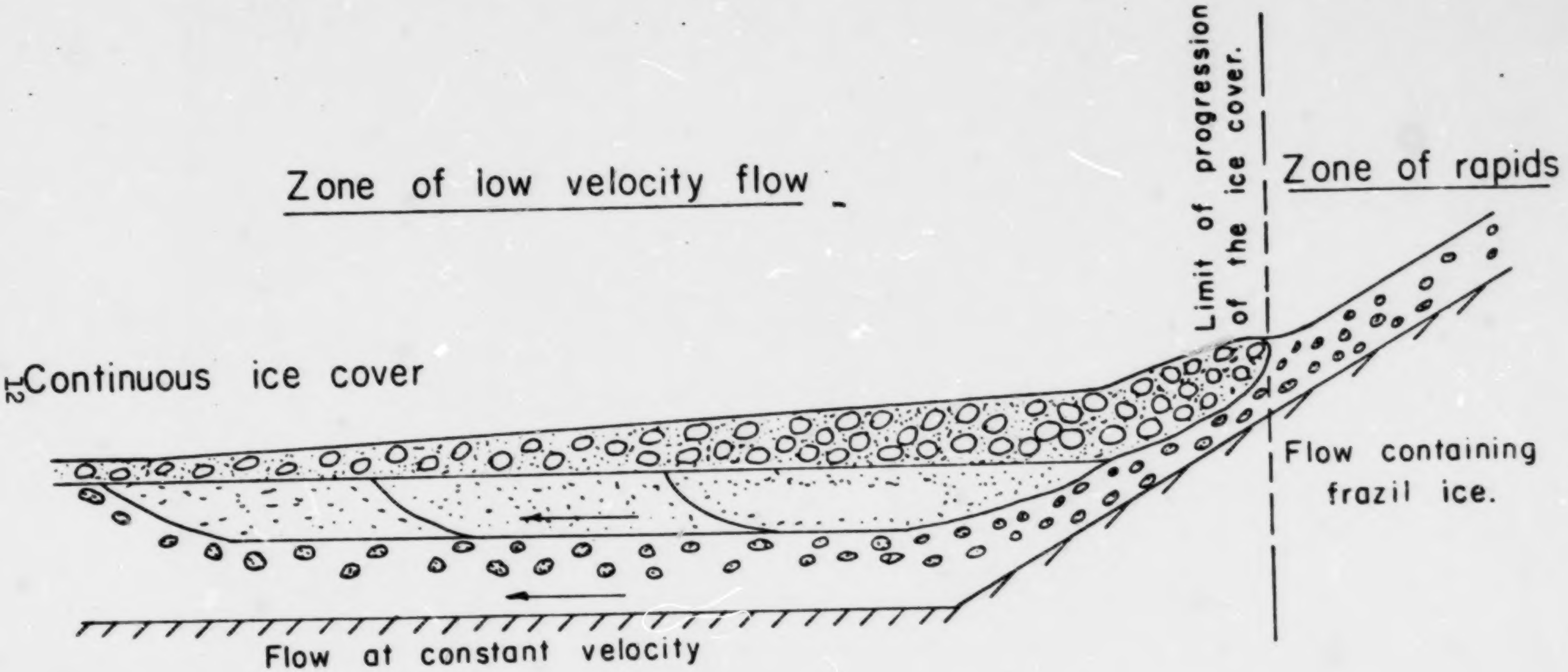
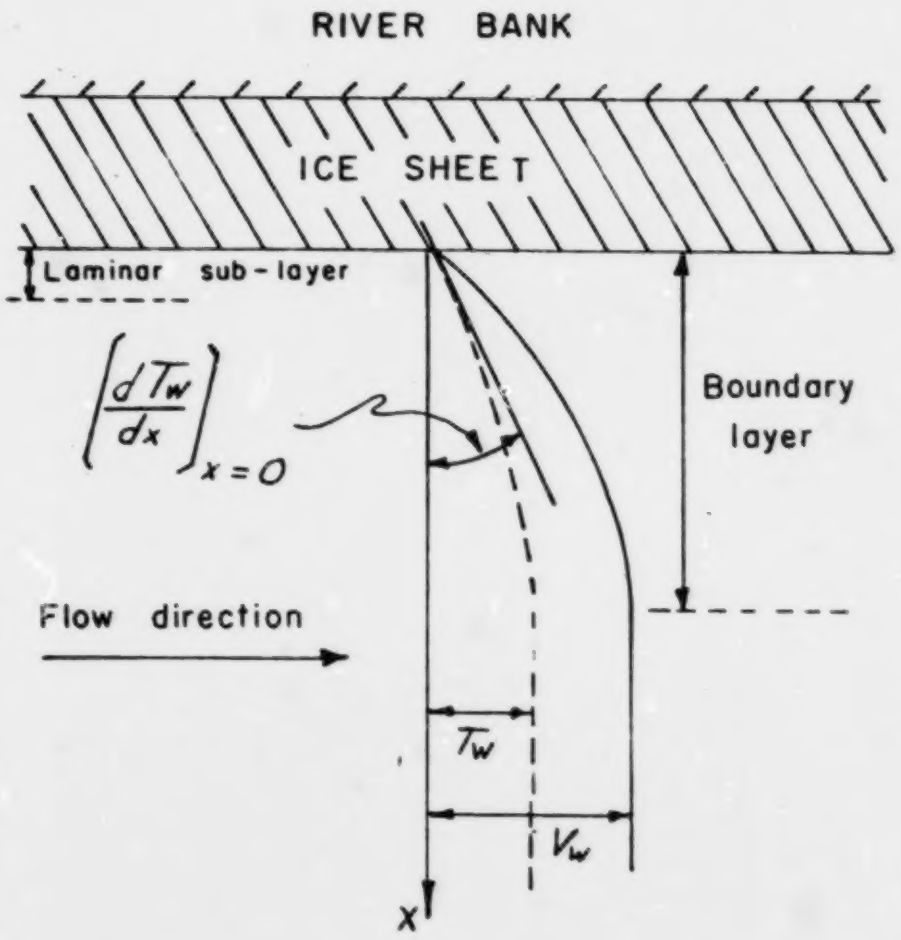

Zone of low velocity flow
Zone of rapids
Limit of progression of the ice cover.
12
Continuous ice cover
Flow containing frazil ice.
Flow at constant velocity

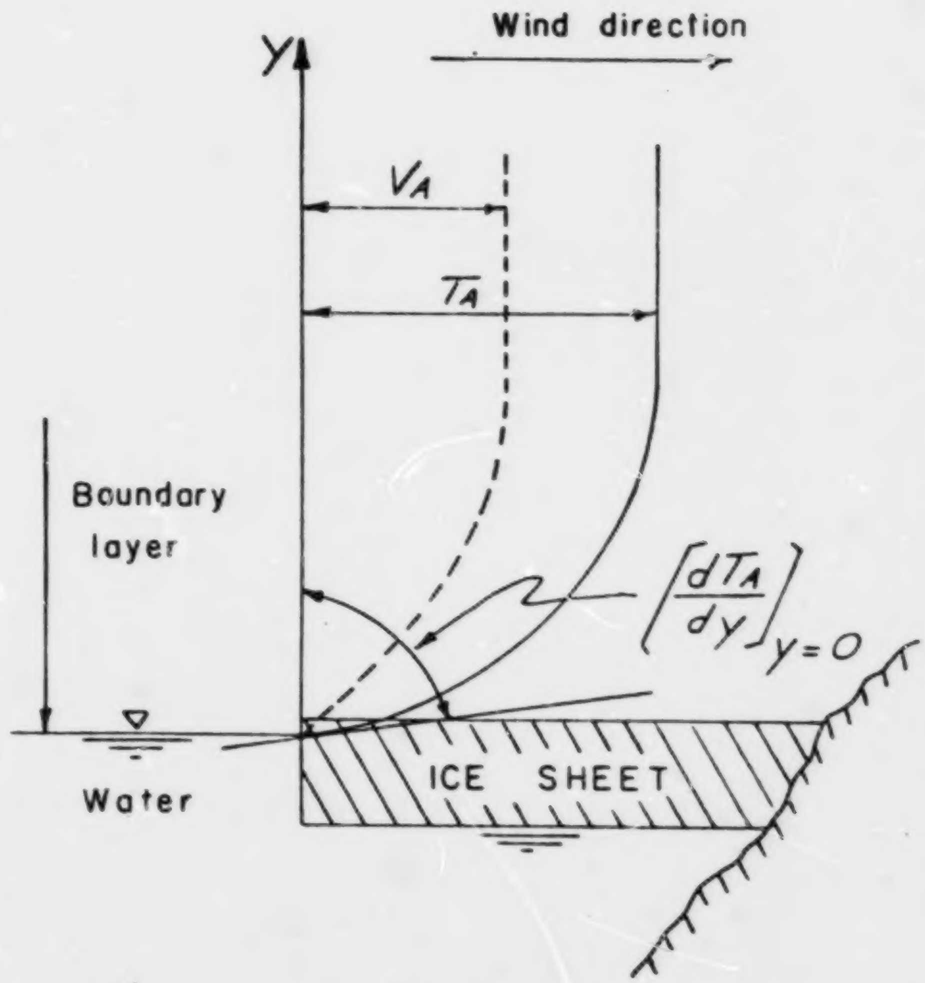
FIG. 6 — ICE JAM AT THE FOOT OF RAPIDS AND PROGRESSIVE DOWNSTREAM DEPOSIT OF FRAZIL ICE.

(Michel, 1966)


RIVER BANK
ICE SHEET
Laminar sub-layer
$\left[\frac{dT_w}{dx}\right]_{x=0}$
Boundary layer
Flow direction
T_w
V_w
X

V_w : water velocity.
T_w : water temperature.

FIGURE 7. (Michel, 1966)


Wind direction
Y
V_A
T_A
Boundary layer
$\left[\frac{dT_A}{dy}\right]_{y=0}$
Water
ICE SHEET

V_A : air velocity (wind).
T_A : air temperature.

FIGURE 8. (Michel, 1966)

transfer to velocity distribution, if the water temperature is higher than the freezing point, there is also a temperature gradient of similar form from the warm water temperature at the reference point outside the boundary layer to the freezing point temperature at the ice boundary. The quantity of heat that the warm water is giving to the boundary is:

$$Q_w = K_w \frac{dTw}{dx}_{x=0}$$

where K_w is the thermal conductivity of water.

"Consider now, in a direction normal to the ice sheet at the ice boundary, the wind velocity profile in air (fig. 8). Without taking into account the heat extraction from water by radiation or evaporation, the quantity of heat taken out by convection from a thin surface film of water at the ice boundary will be, for similar reasons:

$$Q_a = K_a \frac{dTa}{dy}_{y=0}$$

where K_a is the thermal conductivity of air.

"The ice border will grow if Q_a is higher than Q_w. Because of the values of K_w and K_a, the air temperature gradient at the boundary has to be about 25 times higher in air than in water. But wind velocities and air temperature differences below freezing are often so much higher in winter than water velocities and water temperature above freezing that the border ice will progress even in warm water if the weather is cold enough. Of course this growth will be accelerated if the water temperature in the turbulent flow itself is already at the freezing point.

"In strong rapids where usually an ice cover cannot be formed, very cold weather will provoke the formation of a continuous ice cover from one bank to the other, especially if many rock boulders emerge around where the border ice growth process is also produced.

"From measurements made on Norwegian rivers (Devik, 1964) during periods of intense cold, it was possible to establish a curve giving a combination of surface velocity - water temperature where either an ice cover will form or open water will exist (fig. 9). We can see that an ice cover may exist even at high surface velocities, by the border ice growth process.

"Water levels and discharges in rivers as connected with those processes

"Ice is also formed (Devik, 1964) on underwater objects and is called anchor ice, as is well known. The coating of anchor ice may be several inches thick and may tend to grow more rapidly in sharp corners. This causes the irregularities in the stream bed to be accentuated, and this anchor ice may eventually dam up the stream. Thus it is possible

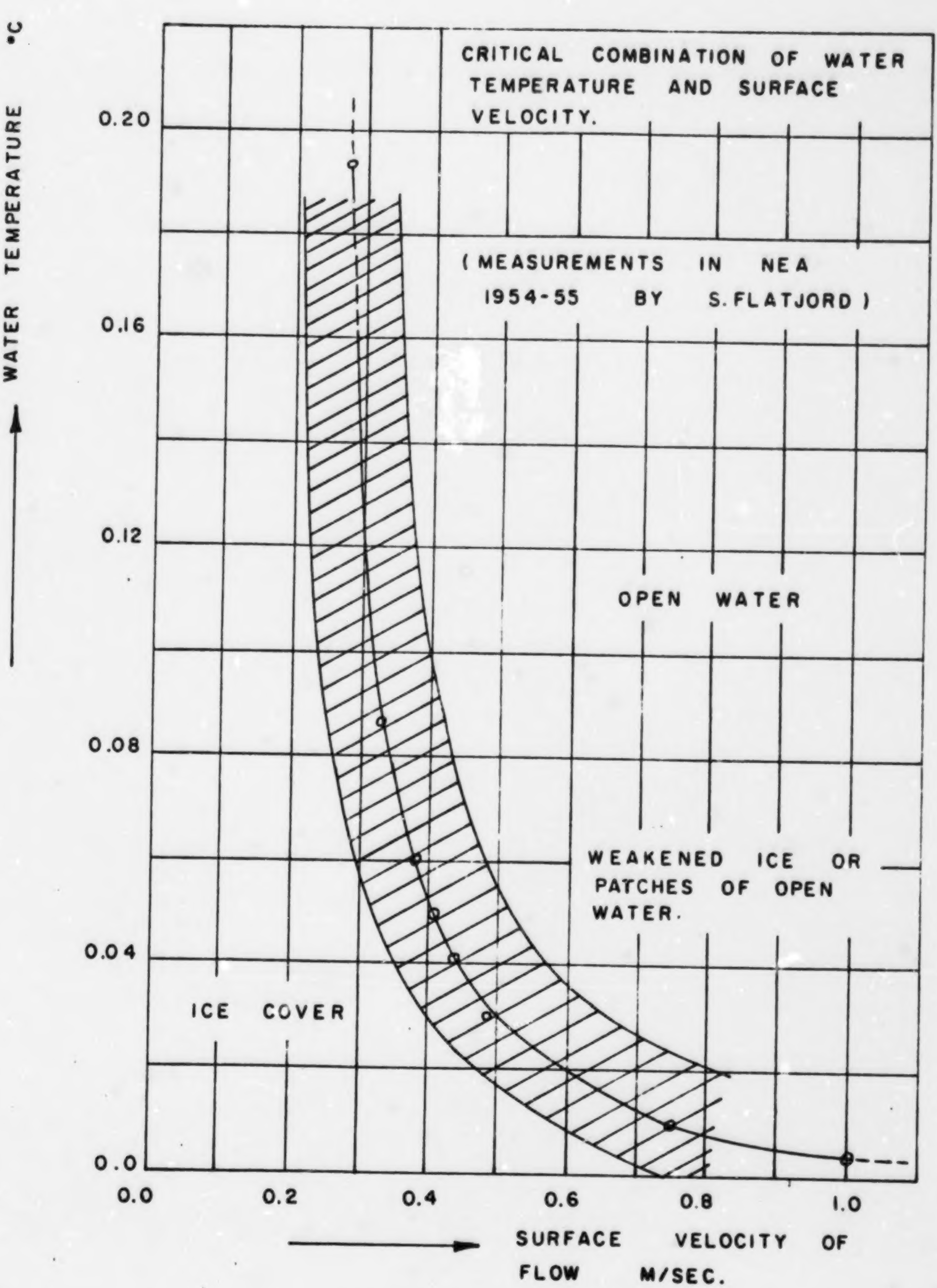


FIG. 9 (Michel, 1966)

to develop a staircase of a series of small ice dams with some still water trapped behind them. The increased viscosity due to the ice content, the damping of turbulent eddies, and the rise of the river bed due to the formation of anchor ice also cause a slight increase in river stage.

"When an ice cover on the surface is complete, the river regime changes from open-water flow to flow beneath the ice cover. The frictional losses against the rough undersurface of the ice reduces the mean velocity, and the river stage must rise in order to pass the same volume of flow. The rise in stage in turn may place a large volume of water in temporary storage and causes a temporary decrease in discharge."

In a similar paper, Michel and Triquet (1966) analyze the ice cover of the Chaudiere River. The frazil ice evolution process described is similar to the one analyzed by Laszloffy in the following paper.

Laszloffy (1948), in one portion of an extensive study, describes the mechanics of ice formation, growth and decay.

"The purpose of the present study is to sketch a summary of ice conditions in rivers, based partly on observations made in Hungarian rivers and partly taking into account the research conducted in eastern and northern Europe as well as in North America."

He discusses river ice formation, floe movement, freezing of the river and breakup. The following material is most directly associated with ice jamming.

"The movement of floes

"The floes drifting on the surface of the water bump against one another unceasingly. They become round and there is formed about their periphery a flange which plays a very important role in the process of their growth. In fact, because of this flange, or rim, each floe assumes the shape of a shallow plate. Now, these plates collide with one another, plunge into the water, and fill themselves with water which, once frozen, builds up the ice floes. On the other hand, on account of these flanges, the contact surface of thin ice becomes larger, facilitating its freezing (fig. 2), so that the diameter of the drifting floes increases very rapidly, soon covering the entire surface of the river.

(a) The principles relative to the movement of floes have been expressed in mathematical form by Schoklitsch (1930): If... 'B' = width of the water surface; 'v' = the average velocity at the surface; '$\sigma < 1$' = the portion of the water surface occupied by the ice and hereafter designated 'degree of ice cover'; we obtain the quantity of ice that passes through the consecutive cross sections '1' and '2' of the river by the formula:

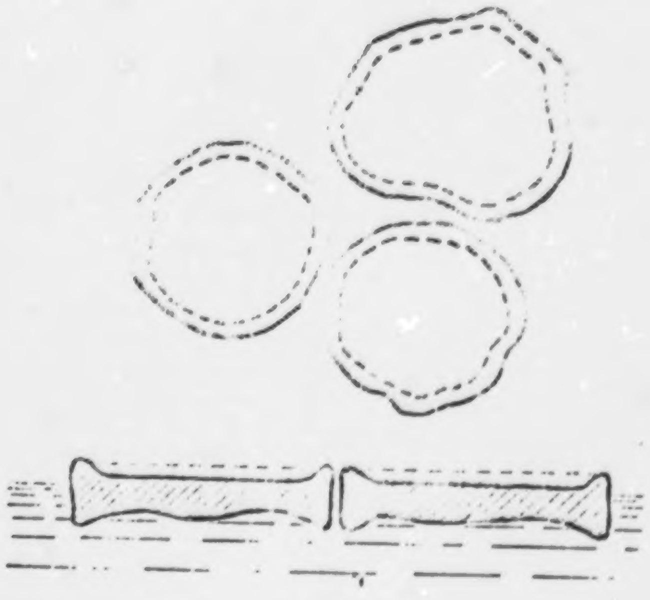


Figure 2.
Characteristic form of ice flocs
(Laszloffy, 1948)

$$\sigma_1 B_1 v_1 = \sigma_2 B_2 v_2 \text{ (sq m/sec).} \qquad (1)$$

This formula signifies that, in the case of a constant advance of the ice, the product of the three quantities is constant at every point of a river reach, otherwise the change of any one of these quantities necessarily changes the other two...."

(b) The slope of a stream progressively flattens from its source toward its mouth.... Considering that the velocity decreases in proportion to the decrease in slope, the formation of the ice continues to increase from the source toward the mouth of the river ... and, at the same time, the degree of ice cover has a progressive tendency.

(c) The degree of ice cover is also modified as a result of the configuration of the channel. The floes advancing within the sharp curves of the river not being able, by reason of their inertia, to follow the current that passes at the point of inflection from one side to the other, remain along the side of their approach. For this reason, they are grounded over the shoal (convex side) of the next curve, at the same time contracting the cross section of flow (fig. 3)....

"The floes coming to rest at the points of the shoals and islands, contribute also to contracting the crossing (fig. 4). By reason of the contraction of the channel by the floes as well as the decrease of depth and velocity due to the bifurcation of the channel upstream of the point of the island, a local increase of the degree of ice cover is produced."

"The freezing of the river

"Whenever σ , the degree of ice cover, becomes equal to or greater than unity, that is, if the surface area of the floes arriving within the unit of time is greater than the free surface of the water having to be passed during the same time, the ice perforce accumulates and comes to rest (jams). The stoppage may also be produced as a result of mechanical causes, even if σ is less than unity, in the case where the accumulating ice finally assumes the form of a bridge."

"The breakup

"... This breakup, however, is quite different from the calm movement of ice floes that precedes the freezing of the river. No longer is it a matter of round ice floes uniformly distributed over the surface of the river, but of large, irregularly formed blocks of ice which the flowing waters carry along under the still solid ice sheet that they encounter ahead of them. The debris of the ice cover is swept along by the current and wherever ice has packed together and strengthened itself, at the time when the river froze, or where the flow section of the river

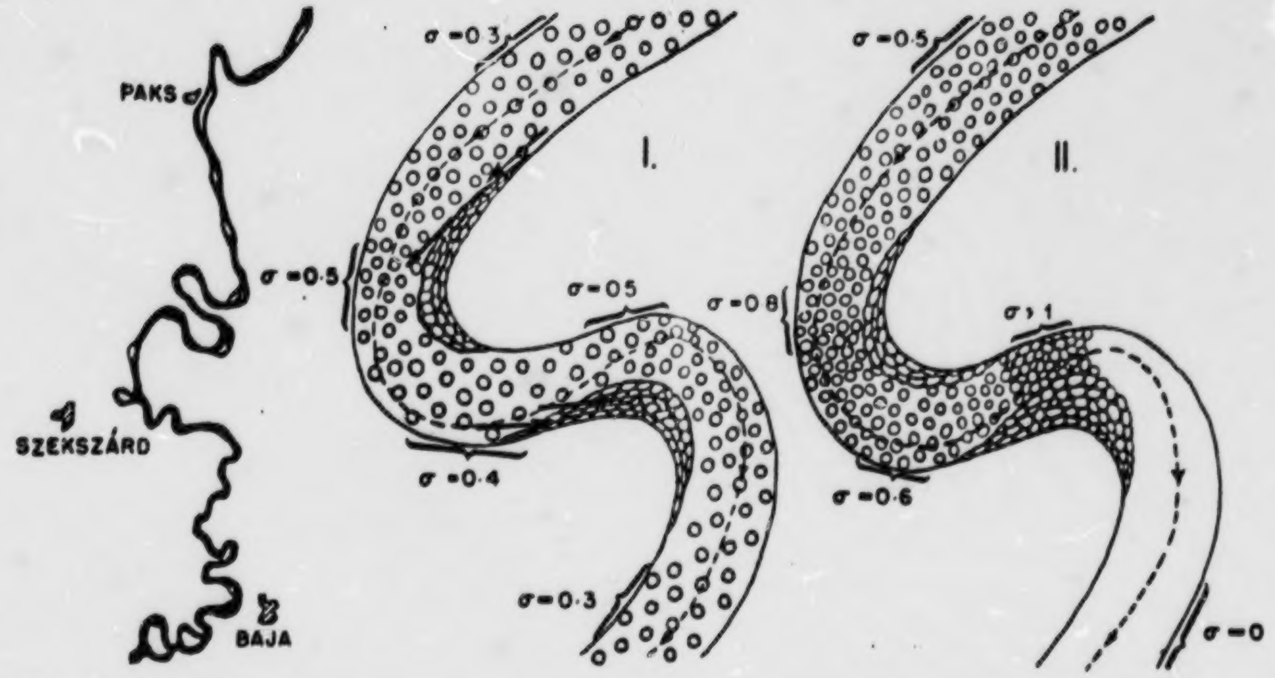

PAKS
SZEKSZÁRD
BAJA
σ = 0.3
I.
σ = 0.5
σ = 0.5
σ = 0.4
σ = 0.3
σ = 0.5
II.
σ = 0.8
σ > 1
σ = 0.6
σ = 0

Figure 3. The part played by river bends in the accumulation of ice. At left: typical bends of a reach of the Middle Danube (Kilometers 1470 to 1540) before regulation. (Laszloffy, 1948)

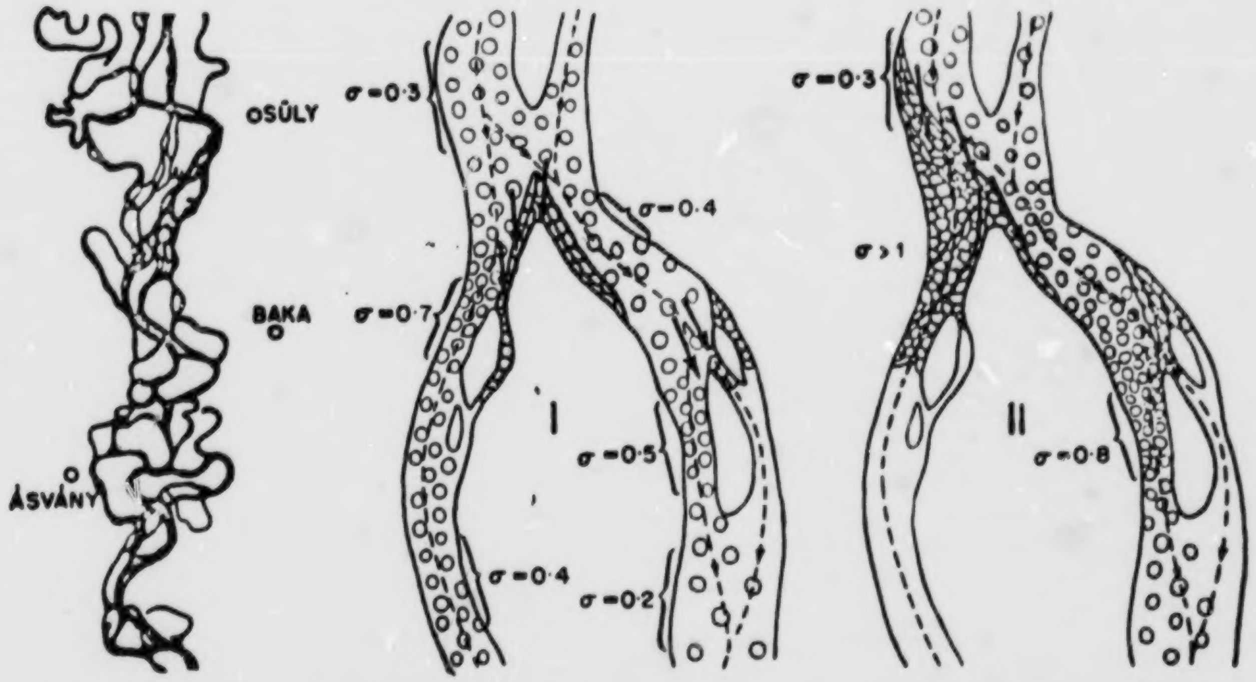

OSÚLY
BAKA
ÁSVÁNY
σ = 0.3
σ = 0.4
σ = 0.7
I
σ = 0.5
σ = 0.4
σ = 0.2
σ = 0.3
σ > 1
II
σ = 0.8

Figure 4. The part played by shoals and meanders in the accumulation of ice. At left: reach of the Danube downstream from the confluence of the Morava-March (Kilometers 1810 to 1835) before regulation. (Laszloffy, 1948)

is already considerably contracted, the flow obstructs its own channel....

"The narrow flow sections permit the water to flow only under an enormous pressure, which is produced by the backwater caused above dams and ice jams. The water level continues to rise until:

(a) There is sufficient pressure to expel the water beneath the ice,

(b) or else until the water finds another channel by-passing the obstruction to flow. The more deeply the bed of the river is incised, the more probable it is that situation (a) will be produced.

"The height of stages caused by the ice jams cannot be computed, because it is a function of the most diverse factors (configuration and condition of the bed, meteorological and hydrological conditions both momentary and earlier, shapes of the ice blocks, etc.)....

(1) The lower the water level at the time the river freezes (hence, the narrower the flow section beneath the ice sheet),

(2) the colder and more prolonged the winter (hence, the thicker the ice),

(3) the more violent the thaw (hence, the greater the discharge),

(4) the flatter the slope of the river (hence, the lower velocity),

(5) the less deeply the river channel is incised,

(6) the more deteriorated the channel,

the more dangerous is the breakup.

"The disintegration of ice is by no means a gradual processing from the source of the river to its mouth. It is produced simultaneously over a number of reaches. Because of the general thaw every tributary is swollen so that the melting of the surface ice and its disintegration commence at the same time at the mouth of every important tributary. Unless the places of confluence are not very near, it is only in the reaches between two tributaries that the ice will be able to accumulate. From the standpoint of ice conditions, it is always the longest reach that brings about the greatest dangers, that is to say, the reach along which the mouths of the tributaries are spaced farther from one another. It follows from all this that the most dangerous ice jams are formed on the downstream part of these reaches, just upstream from the confluence of the tributaries."

"We have stated that the present study is confined to qualitative statements. Ice conditions cannot be expressed in quantitative terms because, as we have seen, they deal not only with thermodynamic phenomena but also with decisive mechanical factors (configuration of the channel). For climatic reasons, ice conditions in the rivers of the U.S.S.R., for example, are different from those of the rivers of western Europe; and, for geographical reasons, these conditions manifest themselves in an entirely different manner in the streams of the different regions of the same climatic zone. Furthermore, ice conditions change even within the same reach of a river, because the condition of the channel, exerting an influence upon the stoppage of ice, is not uniform."

Field data are added to support the above theories in later sections of this paper.

Triquet (1965) quotes Laszloffy extensively and makes the following comments.

"... Thus, he affirmed that rhythm of ice formation is more rapid at the start of winter than later on because the water clears itself: this statement is difficult to verify. He also, noted that the formation of ice is facilitated by the presence of objects and established constructions in the water: this does not appear very clear. He wishes without a doubt to say that this formation is facilitated by the presence of constructions restricting the flow.

"In his definition of ice floe... he speaks of a process by which the ice floes are submerged in the water and thereby filled with water, which freezes, re-enforcing the ice floes. We have never observed such a phenomenon: on the contrary, to our knowledge, the ice floes are always held at the surface of the flow.

"He also affirms that the formation of ice increases from the source toward the mouth: taking this affirmation in context, he probably wishes to speak of the formation of the ice field. In practice this is not realized, at least in a categoric fashion; the sections of initiation of the field are spread out over the entire water course and the formation of the field is begun simultaneously in several places."

Berdennikov (1964) presents an analytic scheme for calculating normal compressive stresses of a broken-up ice field. He compares the calculations with field data in order to determine some dynamic conditions of ice jam formations.

"General conditions

"During the period preceding the opening up of a river and clearing of ice, the dynamic interaction between the streamflow of water in the river and the ice cover is characterized by an increase in the energy of streamflow, which is manifested by a rising stage and increased discharge, as well as by a weakening of the strength of the ice cover, which is revealed by lesser adhesion to the banks and decrease of the ultimate strength, with an increasing fluidity of the ice itself. This interaction, generally speaking, is defined by the expression

$$P_m + W + P_v + Q_i + F_v - P_\sigma - T = 0, \qquad (1)$$

where:"

P_m = thrust against ice cover edge by ice from the upper reaches;
W = the friction force of the wind;
P_v = the total hydrodynamic pressure against the leading edge of the ice cover;
Q_i = the weight component of the ice masses (parallel to the water surface), proportional to the slope of the water surface;
F_v = the friction force of the water under the ice cover;
P_σ = the normal component to the cross section of the ice stresses;
T = the tangential stress component caused by the friction of the ice against the banks.

"The two latter forces enter into the expression (1) with a negative sign, since they correspond to the counterpressure, that is, to a reaction in relation to the main moving force of the current. The P_m value can be evaluated when the velocity of approach to the edge is known, as is the mass of ice floating in one second (ice discharge). The value W is usually assumed as being proportional to a square of the wind speed, while the values of the coefficient of proportionality can be found in Karaushev (1962). The values P_v and Q_i are easily calculated....

"It is necessary to note the structure of the expression for the frictional force of the water under the ice cover, which is in the final count a determinant for the process of the opening up of rivers. In spite of the fact that the problem of calculation of this characteristic is far from new, nevertheless its valid solution is available only for ideal condition, when the ice roughness is equal to the roughness of the river bed, while the streamflow is uniform. In this case, the expression

$$\tau = \frac{\gamma v^2}{C^2} \qquad (2)$$

is true, where τ is the shearing stress on the river bed (bottom) and the bottom surface of the ice, V is the mean velocity of the current, γ is the specific weight of the water, and C the Chezy coefficient.

"In most cases, it is necessary to take into consideration the different roughness of the ice and of the bottom. V. M. Makkaveyev ... divided the stream flow along the vertical into two zones by an imaginary horizontal plane passing through the point of maximum of the velocity curve. For the upper zone,

$$\tau_i = Hi\gamma\beta, \tag{3}$$

can be written, where τ_i is the shearing stress of the frictional force at the lower surface of ice (t/m^2), H is the depth of the layer of water under the ice (m), i is the slope, β is a part of the total frictional force acting on the ice cover. For the calculation of the frictional force of the under-ice streamflow, according to expression (3), a nomogram of values of β, adduced in (Karaushev, 1962), may be employed. For that purpose the values of the Chezy coefficients which correspond to the zones near the ice and at the bottom, are first calculated:

$$C_i = \frac{1}{n_i}\left(\frac{H}{2}\right)^{\frac{1}{6}} \text{ and } C_0 = \frac{1}{n_0}\left(\frac{H}{2}\right)^{\frac{1}{6}}, \tag{4}$$

where C_i and n_i are the Chezy coefficient and the coefficient of roughness for the ice, and C_0 and n_0 are the same coefficients for the bottom.

"The most complex and least studied problem is that of taking into consideration the components P. and T, which enter into the basic expression (1). During the period of the destruction of the ice cover, in the process of which investigation of the relationship between the forces is of practical interest, the ice gradually changes from its winter monolithic state to a state of separate ice blocks.

"Thus, we confine ourselves to a discussion solely of the dynamic conditions of a period when only those strains and stresses appear that enter into the basic equation (1)....

"Maximum stressed state of a broken up ice field

"Let us assume that in a certain reach of the river an ice jam is formed. By appearance this condition is characterized by the fact that as a result of shifting the ice cover has been separated into individual ice fields and fragments of fields, or ice floes.

"First of all, the forces acting along the axis of the streamflow and in the lateral direction must be investigated. The simplest expression of the forces for a case of the absence of friction between the broken up ice field and the banks, with the ice thickness being equal to the unit, appears in the form of

$$P_x = 1x\tau_1, \quad P_y = \xi P_x = \xi \cdot 1x\tau_1, \tag{5}$$

where P_x and P_y are, respectively, the stresses per unit of the width along the axis of the streamflow, and in the perpendicular direction, τ_1 is the tangential stress of the friction of the ice in relation to the water, x is the coordinate in the direction of the current, measured from the upper edge of the ice field, ξ is the coefficient of the lateral pressure....

"It must be pointed out that the effective load is applied not to the center of the cross section of the ice field, but to its lower surface. Therefore, simultaneously with the normal stresses, an overturning moment also takes place. Owing to the small thickness of the ice as compared to the length of the ice field, the overturning moment is relatively weak. Therefore, the force P_x can with sufficient adequacy be assumed as some average normal stress q_x multiplied by the thickness of the ice field. As to the stresses P_y acting in a direction perpendicular to the streamflow axis, this value in expression (5), by analogy to a friable medium, is determined by the value of the stress in the direction of the current multiplied by coefficient ξ ....

"In determining the value of the coefficient of the lateral pressure, one should keep in mind its dependence on the strength and deformation properties of the ice field, as well as on the nature of the contact between the ice and the banks. Thus, one of the expressions for the coefficient in question appears as

$$\xi = \frac{\mu}{1-\mu}. \tag{6}$$

where μ is the coefficient of the lateral expansion (Poisson's ratio).

Expression (6) corresponds to the stressed state of an ice field within the elastic limit of the ice. Under the natural conditions of rivers, the value of the coefficient of the lateral pressure is affected significantly by the steepness of the banks, since, as a result of ice floes being pushed out onto the banks, the lateral pressure diminishes. Stronger ice is usually accompanied by higher lateral pressure. To put it more precisely, when evaluating the possible values of ξ , one should take into consideration the relationship between the strength of the ice and the intensity of the pressure developing along the stream axis. Under the conditions of limiting stressed state, the following expression, as is well known (Sokolovskiy, 1960) holds true

$$\xi = \mathrm{tg}^2\left(45° - \frac{\varphi}{2}\right). \qquad (7)$$

where φ is the angle of internal friction.

"... Let us now examine the case of an ice field when friction against the banks is present.

"Let us imagine a river reach where there is a broken ice field. Let us select the origin or the coordinates at its upper edge, and the direction of the abscissae axes and ordinates, respectively, parallel and perpendicular to the center line of channel. Let us examine the forces acting upon an element of the ice field, the length of which is d_x (Fig. 1, shown crosshatched). These forces are the following: the component of the normal stress along the streamflow axis, effective in both the cross sections, but of different intensity and in opposite directions; the gravity component; the tangential stress of the friction of the water against the ice, and the frictional force of the ice against the banks, proportional to the lateral pressure. The equilibrium of the forces acting upon the element is defined by the following expression

$$(q_x + dq_x)Bh - q_xBh - \tau_1 B\,dx + 2\xi fhq_x\,dx = 0, \qquad (8)$$

where... f is the coefficient of the ice friction against the banks, h is the ice thickness.

"The ice field is assumed to be uniform in its thickness throughout. After reduction, rearrangement... and following integration... for boundary conditions of q_x = 0 and x=0, we obtain the final form

$$q_x = \frac{\tau_1 B}{2\xi fh}\left(1 - e^{-2\xi f\frac{x}{B}}\right). \qquad (10)$$

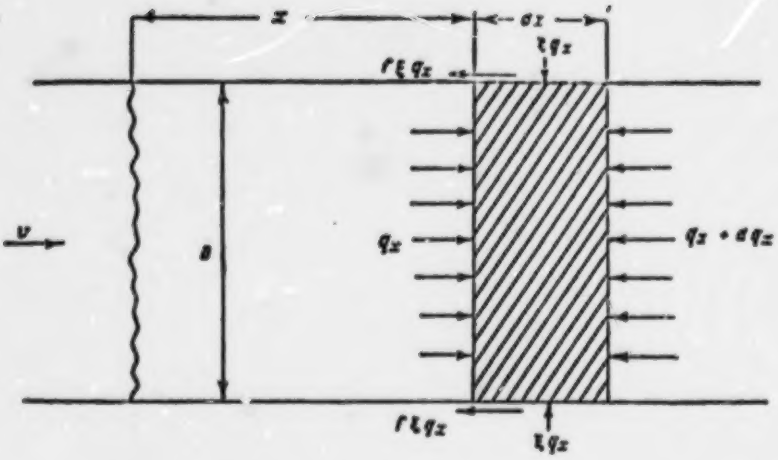

x
dx
ξq_x
fξq_x
v
B
q_x
q_x + dq_x
fξq_x
ξq_x

Fig. 1. Stresses acting upon an element of a broken up ice field. (Berdennikov, 1964)

"Taking into consideration that the ratio between the normal stresses is defined, as before, by the coefficient of lateral pressure, we obtain

$$q_y = \frac{\tau_1 B}{2fh}\left(1 - e^{-2\xi f \frac{x}{B}}\right). \tag{11}$$

"Equations (10) and (11) derived in this manner make it possible to calculate the normal stresses of a broken up field. In order to determine in some specific case of ice jam the degree of approximation to a limiting stressed state, the calculated values of the normal stresses q_x and q_y are compared to the characteristics of the ice strength, which will be discussed later.

"From the structure of expressions (10) and (11) it is apparent that the increase of the normal stresses occurs over a limited sector of the ice field length. With increase of its length, the stresses approach asymptotically a definite limit, for which the expression can be written in the following form:

$$q_{max} = \frac{\tau_1 B}{2\xi fh} \quad \text{with} \quad x \gg B. \tag{12}$$

"It must be kept in mind that the absolute value of the normal stress, determined by expression (12), as well as the scale of the ice field lengths over which this value is attained, depend closely on the values of the coefficient of lateral pressure ξ . In a case where one is examining the stressed state of an ice cover within the elastic limit of the ice, coefficient ξ possesses a maximum value, which is defined by expression (6).

"The condition of the ice during an ice jam is characterized by a stressed state of the ice masses, which is near the critical, and at the time of the breaking up of the ice jam-by a maximum stressed state. The coefficient ξ then possesses a minimum value determined by expression (7). The angle of internal friction φ in formula (7) determines the effect of the action of the friction of the ice against the banks, and also, as will be shown later, the strength characteristics of the ice masses in the ice jam.

"The effect of the action of the internal and boundary friction on the pressure distribution along the vertical and horizontal for friable materials was investigated earlier (Janssen 1895).... In their form, the design formulas being used in structural mechanics for the above calculations are analogous to expressions (10) and (11).

"The conditions of the strength of nonuniform solid bodies, taking into consideration the internal friction... has been greatly developed by A. I. Botkin (1940). According to the present concepts, for a shift along a definite critical elementary area in a brittle or nonuniform solid body, the condition of stability can be expressed in the following form:

$$\tau_n < p + \sigma_n \operatorname{tg} \varphi, \qquad (13)$$

where τ_n is the critical tangential stress; p-the parameter characterizing the interparticle cohesion of the body; σ_n -the normal stress; φ -the angle of internal friction.

"For the ice cover during various stages of its destruction process most of the change affects parameter p. At the very beginning of the ice cover destruction process, parameter p possesses the predominant value for an evaluation of the strength, while for a broken up ice field this factor has no effect whatsoever. On the other hand, if interparticle forces are absent (p=0), a broken up field can withstand considerable loads in the presence of normal compressive stresses or pressure σ_n . In such a case, parameter $\operatorname{tg} \varphi$ will represent some sort of strength characteristic. However, the effect of this parameter is fully determined by the pressure. In the absence of the compressive forces, or in the presence of tensile forces, a broken up ice field offers no resistence. It takes part in the transporting movement together with the streamflow.

"Determination of the parameters and comparison of the calculated values of the pressure ice to factual data

"To determine the parameters of formula (10), let us use the measurements of the tension of an ice boom cable (Latyshenkov, 1946). As is well known...

$$F = \frac{B^2 P}{8s}. \qquad (14)$$

where F is the tension of the boom cable (kg), B is the span (distance) between the anchor-points of the cable equal to the width of the river (m), P is the ice load to a unit of the ice boom length (kg/m), s is the sag of the cable (m).

"The tension of the cable holding an experimental boom on the river Pekhorka was measured with varying lengths of a monolayered broken up ice field. The river was about 10 m wide.

"It must be pointed out that the actual thrust from ice was produced by the friction of water against the bottom side of the ice, and by the hydrodynamic pressure upon the trailing (back) edge of the ice field, whereas when deriving formula (10) we took into consideration only the friction of the water. Latyshenkov (1946) contains a reference to the fact that the friction of the water comprised 85-95% of the combined amount of the load. Therefore, the factor disregarded in formula (10) could not produce any appreciable effect on our calculations. At the same time, in order to eliminate any possibility of error, the results of these measurements (Latyshenkov, 1946) when compared to formula (10) were used only to such extent that the factor of the action of the external load, expressed in formula (10) by the multiplier τ_{ke} , would be excluded from the comparison.

"An examination of the graphic relationships adduced in Latyshenkov (1946) shows that the thrust produced by the ice upon the boom increases with an increase in the length of the ice field held back by the boom up to three or four times the width of the river, beyond which it remains constant. We assumed the limiting value of the load as equal to the unit, and expressed the load value corresponding to a length $L<4B$, in parts of the maximum value (q_x/q_{max}). In this manner, the solid lines in the graph (Fig. 2) show the relation to the relative length of the ice field (x/B).

"Assuming the numerical value of the product ξf = 0.5, let us plot in Fig. 2 a curve of the values of q_x/q_{max} calculated by formula (10), which was found to be in good agreement with the data of the actual measurements....

"Equation (10) then acquires the following, simplified, form

$$q_L = \frac{\tau_1 B}{h}\left(1 - e^{-\frac{L}{B}}\right). \tag{16}$$

"No general meaning can be attributed to equation (16), inasmuch as the evaluation of the product ξf is based on a single specific example of observations with the boom on river Pekhorka. Nevertheless, the conclusions made in this case to the effect that the ice thrust upon the boom increases, with an increase of the length of the ice field being held back by the boom, only up to three or four times the width of the river, was later confirmed in other papers, (Ofitserov, 1948; Filimov, 1948; Beccat and Michel, 1959; Torok, 1955) as well.

"So far the foregoing has referred to an evaluation of errors in the determination according to formula (10) of the relative value of the pressure q_x/q_{max}. For an evaluation of the absolute value of the pressure, let us compare the values calculated by formula (12) to the ice loads upon the boom assumed in the instructions (Voyenizdat NKO, 1945). The first

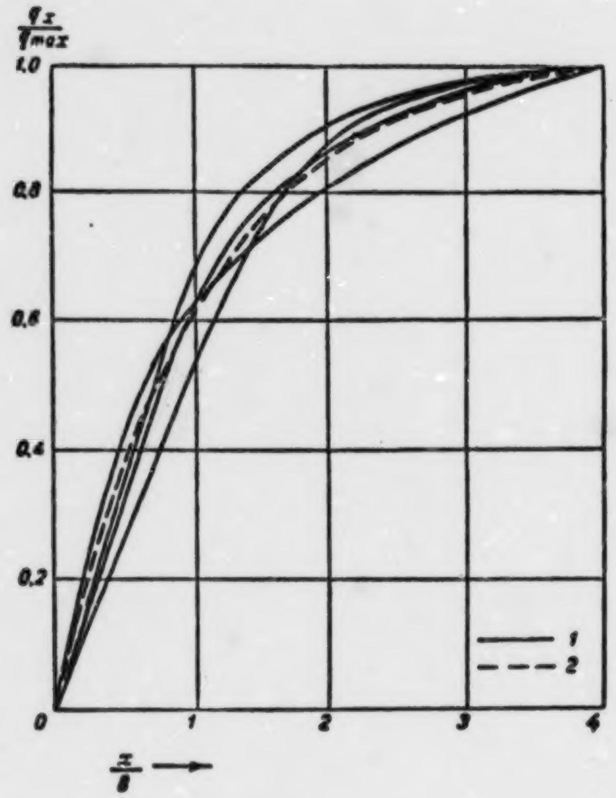


Fig. 2. The relative values of the pressure of a broken up ice field on a boom depending on the length of the field. (Berdennikov, 1964)

1) The factual data according to Latyshenkov (1946)
2) calculated by formula (16).

> three columns of Table 1 show the values of the tension of the cable... for some given river depths and ice thickness, on the basis of which, by means of formula (14), we calculated the values of the ice load for every linear meter of the boom P (column 4). The root-mean-square difference between the loads assumed in accordance with the Instructions and the values of hq_{max} calculated by formula (12) (column 5), was 22 kg/m. In some specific cases the difference does not exceed 37% (column 6). Such a result of the comparison should be regarded as satisfactory."

Berdennikov (1963) analyzes certain phases of the mechanism of formation and breakup of ice gorges using a spring and piston model. He defines two types of ice gorges and confines analysis to the mechanism of formation and breakup of the first type.

> Ice gorges of the first order "... are caused by the... resistance of the ice cover in the process of the initial stage of its opening on some section... and the pressure of the moving masses of ice, as well as the masses of water.... The retardation of the process opening with an ever increasing mass of moving ice and, consequently, with an increase in the pressure developed by this mass at the mass of water, causes a local piling up of ice floes, their turning into an inclined or vertical position, hummocking, underthrusts of one layer under another, and the development of multi-layer pileups by such means."
>
> "A quite different order of ice gorge occurs in the presence of floating ice. They are caused, on the one hand, by the capability of the riverbed and the flow to pass through the ice mass that is coming down from upstream, and, on the other hand, by the volume of the flow of this ice, and also by factors that have an effect on its mobility. For the origin of ice gorges of this order, the hydraulic conditions of the current acquire an special significance, causing ice floes to be carried under the edge of the fixed ice cover (Berdennikov, 1962). Conditions corresponding to carrying ice floes under the edge and the formation of ice gorges are created not only when the ice cover in some place on the river is still preserved in its entirety after the winter, but, on the contrary, cases are not rare when the phase of the opening of the river has already passed. However, the changed conditions of the passage of ice in some section (may) again cause difficulties in the ice flow and in clearing the river of ice. As a consequence of the circumstances mentioned, ice gorges may be repeated twice or more in one spring period in one and the same river section. We will call these phenomena second-order ice gorges."

After a description of processes which weaken spring river ice covers, he describes ice-cover shifts.

> "We should especially note the sharply uneven, impulse nature of the motion of the ice masses during the period of the shifts, and their momentary energy... usually subsides quite rapidly. After such a flareup or burst of energy of the motion of the ice masses, this motion

Table 1

Ice Load Upon a Boom (kg/m), Calculated by Formula (12) and Assumed in the Instructions [6], With Values $v = 1.0$ m/sec, $B = 100$ m, and $s = 0.3\ B$

Data of Instructions [6]			Load per one lin. meter P kg/m 4	By formula (12) hq_{max} 5	Difference in per cent of hq_{max} 6
Depth, m 1	Ice thickness, m 2	Tension of the boom cable F Kg 3			
2,0	0,15	2350	59	94	37
3.0	0,15	2030	52	82	37
4,0	0,15	1910	48	74	35
6,0	0,15	1810	40	59	30
2,0	0,25	3020	75	98	24
3,0	0,25	2400	60	81	26
4,0	0,25	2140	54	72	25
6,0	0,25	1970	49	64	23
2,0	0,5	5000	125	100	—25
3,0	0,5	3550	89	83	—8
4,0	0,5	3020	75	72	—4
6,0	0,5	2400	60	65	+8

Note: Commas in numbers represent decimal points. (Berdennikov, 1964) dies down entirely. For apparently quite incomprehensible reasons the floating masses of ice are held back, although the water masses continue to flow with the same velocity and communicate to the lower surface of the ice a tangential stress that is not less than previously, in the presence of the motion of the ice masses. The period between shifts may be very diverse - sometimes a day or more, especially when chilling sets in and the corresponding increase in the resistivity of the ice cover. A very characteristic feature of shifts on rivers with ice gorges is, together with their periodicity, also the growing power as they approach to some extremal, final moment...."

"The presumption of the possible mechanism of the shifts of the ice cover in the period preceding opening lies in the fact that the basic role is ascribed to various types of friction.... In the motion of ice that has already been split... external friction of the ice floes against the bank and between each other acquires the prevailing significance. In complex hydrological processes such as the destruction of the ice cover and the formation of ice gorges, it would be impossible to define the effects caused only by internal friction or only by external friction, and this is not even required. It is essential to note that both one form of friction and the other form cause a scattering of energy and qualitatively characterize the capability of the ice cover to render resistance to the external stresses and strains acting on it....

"Before we engage ourselves in studying the quite complex mechanism of shifts of the ice cover, let us consider the mechanism of friction in itself (Kharkevich, 1954).... We will assume that any body of ice... is pressed against the flat surface of another larger body and that a tangential force is acting on it.

"The motion of the bodies relative to each other at first is lacking, since on the plane of their contact the force of the friction of rest is acting. The tangential force causes only a strain of the body. When... the elastic force exceeds the force of the friction of rest, a breaking free along the plane of contact occurs, and, with a jump, the body shifts to a new position. In this case, elastic energy is expended to overcome friction...."

"To ascertain the quantitative ratios, we will consider a mechanical system (Fig. 2), which consists of a spring 1 connected with a piston 2. The forward end of the spring A by means of a motor is moved with a small but constant velocity v_0. The piston 2 fits tightly in the walls of the cylinder 3, as a consequence of which its sliding relative to the fixed cylinder is possible only with a considerable effort.

"The motion of the piston in the cylinder can commence only after the force of the elasticity of the spring exceeds the force of the friction of rest. In this case, the piston is moved somewhat on the bias (sic) in accordance with the reserve of the elastic energy of the spring, after which it stops. Then, since the motor operates continuously and the end of the spring A continues to be moved with the same velocity v_0, everything is repeated again.

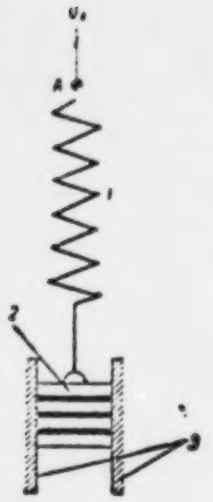


Fig. 2. Diagram of
a mechanical
system. (Berdennikov, 1963)

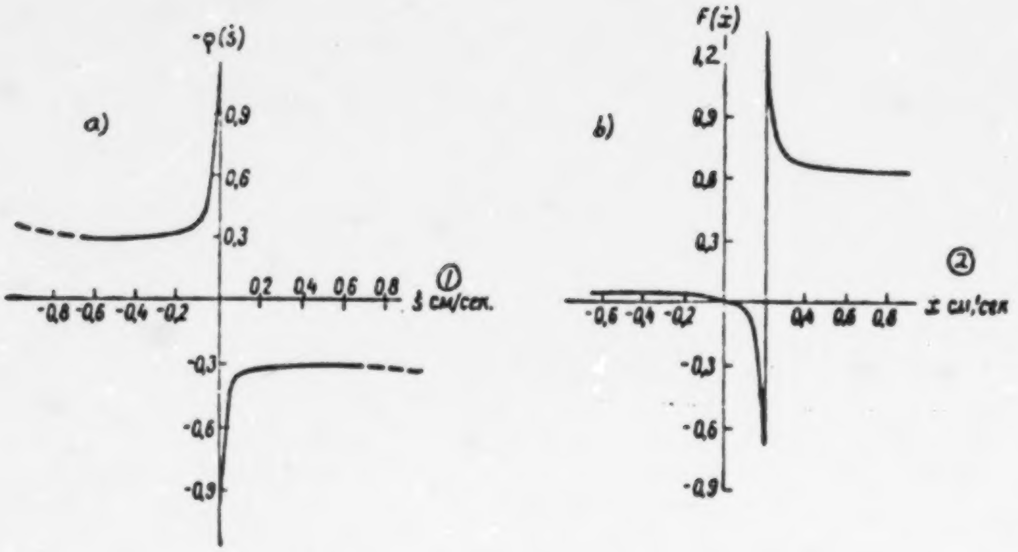


Fig. 3. Illustration of functional dependences.
1) $\dot{s}$, cm/sec; 2) $\dot{x}$, cm/sec. (Berdennikov, 1963)

"We will shift further to a consideration of the dynamics of shifts of the ice cover. In view of the great diversity of the factors acting on the ice cover... the task of establishing a general, universal mechanism of shifts, in essence, is insoluble. Because of this, we will dwell on the consideration of a particular case, which is quite typical. Let some section of the ice cover with a length of several dozen kilometers in a period preceding the opening of the river already have a very weak connection with the banks and therefore it has a certain pliability in the direction of the current. The water flow has a considerable dynamic effect on the ice cover, and especially the moving forms of ice floating toward the edge of the ice cover from sections lying upstream that have already opened. On the other hand, as yet firmer ice still exists at the lower end of the section under consideration, where, for example, there may be a sharp curvature of the riverbed, a constriction of it by islands, structures, etc. Since the connection of the ice cover with the banks in this zone is sufficient to hold it in place in the entire section under consideration, the ice here turns out to be in an elastically stressed state, under the effect of external applied forces. This stress increases as the applied forces grow, and energy of elastic strains is accumulated, until such a time as the limit of the resistivity of the ice cover is exceeded, which limit is determined by the degree of the strength of its connection with the banks, the thickness of the ice, and internal and external friction. At this moment the first shift of the ice cover occurs, the magnitude of which corresponds to the reserve of elastic energy, after which the ice stops. In view of the fact that the external... forces act constantly on the ice, the elastically-stressed state of the ice in the river section under consideration, gradually increasing, after the passage of a certain time again reaches the limit of resistivity, and then again a shift occurs, etc.

"Thus, the process of periodic shifts we have just described has a great qualitative similarity with the action of the models represented in Fig. 2. Therefore, in the future we will work from the assumptions that the phenomena of shifts in the ice cover are identical to the purely mechanical simplified systems...."

"The differential equation of motion for the system mentioned may be written in the following form:

$$m\ddot{\xi} + \varphi(\dot{\xi} - v_0) + k\xi = 0, \qquad (1)$$

where m is the mass of the body being moved, ξ is the tension of the spring, k is the elastic constant of the spring, v_0 is the velocity of motion of the forward end of the spring, $\dot{\xi}$ and $\ddot{\xi}$ are the first and second derivatives of ξ with respect to time, φ is a function of which it is known that its sign is opposite to the sign of the difference enclosed in the parentheses.

"The quantity enclosed in the parentheses is the rate of movement of the piston relative to the cylinder, or the rate of slide ($\dot{s}$)....

"We will note that the equilibrium between the action of the elasticity of the spring and the force of friction will occur upon condition that

$$\varphi(-v_0)+k\xi=0. \tag{3}$$

"In... (Stoker, 1953) it is shown that for a further analysis it is convenient to introduce a new variable x, having replaced ξ in formula (1) by means of the ratio

$$x=\xi+\frac{1}{k}\varphi(-v_0). \tag{4}$$

"The differential equation for x takes the following form:

$$m\ddot{x}+\left[\varphi(\dot{x}-v_0)-\varphi(-v_0)\right]+kx=0. \tag{5}$$

"In brackets is enclosed a new function

$$F(\dot{x})=\varphi(\dot{x}-v_0)-\varphi(-v_0). \tag{6}$$

"With a consideration of this symbol, the basic differential equation for x takes the form

$$m\ddot{x}+F(\dot{x})+kx=0. \tag{7}$$

"This expression is a non-linear second-order equation, which is not solved precisely by known methods.

"In view of the impossibility of a precise solution of equation (7)... we must resort to the so-called method of quantitative integration (Stoker, 1953; Teodorchik, 1952). In such a type of cases, the behavior of the system (Fig. 2) described by the second-order differential equation usually is represented at any moment of time by the position of the representative point (x_0 , y_0) on the so-called 'phase plane of the initial conditions.' Such a phase plane we may consider the plane coordinates x, y, and y = x = dx/dt. In the motion of the system, the representative point moves along the phase plane, describing on it a continuous curve, i.e., the integral curve of the system. Since entirely definite initial conditions correspond to any point on the phase plane, the integral curve passes through any point of this plane, corresponding to an entirely definite behavior of the system originating from the initial conditions. From this rule are derived only points corresponding to positions of equilibrium.

"From the equation of motion of system (7) it is easy to obtain the equation of the family of integral curves. For this, it is sufficient to rewrite equation (7) in the form of a system of two first-order equations

$$\begin{aligned} m\frac{dy}{dt} &= -kx - F(y) \\ \frac{dx}{dt} &= y \end{aligned} \tag{8}$$

and....

$$\frac{dy}{dx} = \frac{-kx - F(y)}{my}. \text{"} \tag{9}$$

"Equation (9) in a geometrical presentation corresponds to the angular coefficient of the tangent to the intergral curve at point (x, y) of the phase plane

$$\frac{dy}{dx} = \operatorname{tg} \alpha = \frac{-kx - F(y)}{my}. \tag{10}$$

"Thus, the coordinates and values of the angular coefficient of the integral curves at any point of the phase plane are determined identically with the exception of the positions of equilibrium of the system, for which expression (10) becomes indeterminate, indicating the indefiniteness of the direction of the tangents at the special points corresponding to the equilibrium of the system (Andronov and Khaykin, 1937).

"From expressions (1) - (10) it is apparent that for an analytic and graphic study of the mechanical systems under consideration, we must know first of all the dependence between the force of friction and the rate of slippage.... If we are speaking about a case of the friction of ice or snow, on the basis of research materials we may affirm that the friction of slippage upon condition of a temperature that is close to zero amounts on the average to about 1/3 of the magnitude of the friction of rest (Pavlov, 1940). The shearing stresses decreases sharply after the transition from the state of rest to the state of motion. This decrease occurs in a narrow interval of speeds of motion, close to zero, which is apparent in Fig. 3, a, where a graph of the function $\varphi(\dot{s})$ is represented by two identical curves (the negative values of this function are plotted above the abscissa axis, and the positive values below). As for the increases of $\varphi(\dot{s})$ at great velocities it is explained by the increase in turbulent losses of the river flow as the velocity of the ice increases. We may affirm that for the range of speeds with which shifts of the ice cover occur on rivers, the values of the tangential stresses caused by the turbulence of the flow are merely a small fraction of the stresses developed because of friction against the bank and the internal friction of the ice. Because of this, an increase in $\varphi(\dot{s})$ in the region of high speeds $\dot{s}$ will be insignificant. In Fig. 3, a, the part of the curve referred to this region is represented by a dashed line. We will note that Fig. 3, a, illustrates the general nature of the quantitative relationship of the change in force of friction of the ice and snow as a function of the rate of slippage or shear. Later on, this function will be refined on the basis of the results of experiments (see Tables 2 and 3).

"Let us assume that the dependence $\varphi(\dot{s})$ is known, and also the value of v_0, the rate of the transfer of the upper edge of the ice cover under the pressure of the moving ice, and for the mechanical system (Fig. 2), the values of the speed of the upper end of the spring. Then, having converted the function $\varphi(\dot{s})$ according to formulas (2), (4), and (6), the function F(x), represented graphically in Fig. 3, b...."

"We will turn further to a construction of the integral curves on the phase surface for equation (7) under the assumption that the characteristics of the system are known to us....

"The specific task is composed of defining the directions of the tangents to the integral curves, which is solved by means of a very simple method, proposed by Lienard (1928). In order to place equation (7) in a form that is most convenient for application of Lienard's graphic method... (Stoker, 1953), instead of t a new independent variable t_1 is introduced:

$$t = \sqrt{mk}\, t_1. \tag{11}$$

"As a result we obtain

$$\frac{d^2x}{dt_1^2} + \frac{1}{k} F\left(\sqrt{k/m}\,\frac{dx}{dt_1}\right) + x = 0. \tag{12}$$

"Introducing, as before, the second variable y = dx/dt$_1$, we obtain a first-order equation

$$\frac{dy}{dx} = \frac{-\frac{1}{k} F\left(\sqrt{k/m}\,y\right) - x}{y}. \tag{13}$$

"Following Lienard's method, at first we construct the curve BDEH (Fig. 4) of the characteristics of the mechanical system on the coordinate plane x, y:

$$x = \frac{1}{k} F\left(\sqrt{k/m}\,\frac{dx}{dt_1}\right). \tag{14}$$

"Later we construct the integral curve AHI.... From any point of the phase plane, such as from point A, for example, we draw a straight line AB parallel to axis x to the intersection with the characteristic BDEH at point B. From point B we drop a perpendicular to the axis x, to the intersection with this axis at point C. The tangent to the integral curve being sought at point A will be perpendicular to the straight line CA that we have found. Therefore, a small segment of the integral curve near point A is drawn... from point C as from the center at a radius equal to CA....

"The points of the phase plane characterized by great values of velocity $y \gg v_0$, give integral curves in the form of twisting spirals because of the fact that in our system the energy decreases, being expended in overcoming friction. On the other hand, at low values of velocity, such a region of values of y occurs in which F(y) is negative. According to the principles of the theory (Andronov and Khaykin, 1937; Stoker, 1953; Teodorchik, 1952), the increment (increasing) motion corresponds to the negative value of F(y)...."

"Together with the presence of two different regions of the phase plane for the decrement and increment motion, obviously, a limiting cycle exists, i.e., an integral curve corresponding to the motion of the figure's image point when $t_1 \rightarrow \infty$. In order to find the limiting cycle, it is sufficient to construct an integral curve from points E, lying in the straight-line segments DE of the characteristic BDEH. In

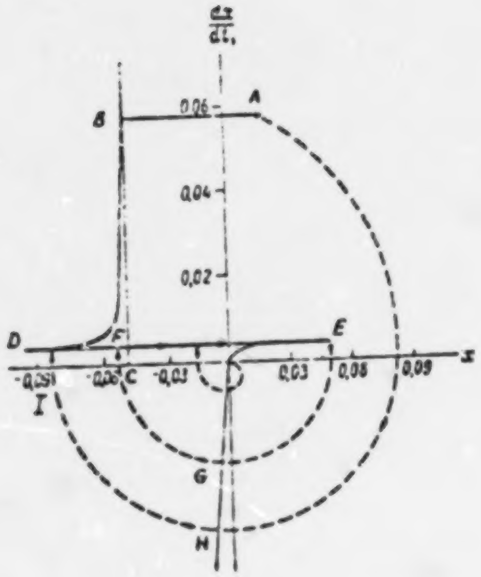


Fig. 4. Illustration of the graphic solution of the differential equation of motion (12) in accordance with Lienard's method. (Berdennikov, 1963)

this case the image point describing the arc EGD, again encountering the segment DE at point F, follows along it from the left to the right to point E, after which the motion in the limiting cycle is repeated.

"According to the determination of the function

$$F\left(\sqrt{k/m}\,\frac{dx}{dt}\right).$$

as long as the elastic stresses do not exceed the magnitude of the friction of rest, according to equation (12), it will be $y = v_0$. The motion of the image point along the horizontal segment DE corresponds to this condition. The moment of the beginning of the slippage of the piston of the mechanical system (see Fig. 2) or the moment of the initial displacement of the ice cover during a shift corresponds to the position of the image point at point E. In the other hand, the meeting of the trajectory of the motion of the image point with the left-hand part of the segment DE is possible and unavoidable in a case when the left end of the segment DE goes adequately far from the beginning of the coordinates or, in other words, when the force of friction turns out to be adequately great....

"In this case, we arrive at the conclusion that an interrupted periodic motion (self-oscillations) is proper to the mechanical system whose characteristics $F(\dot{x})$ are represented in Fig. 3, b.... It lies in the fact that in the presence of a constant (non-oscillatory) source of energy, the mechanical system becomes nevertheless oscillatory as a consequence of the fact that in it there is a special type of regulator, or 'valve', which regulates the entry of energy into the oscillatory system. The role of such a regulator for the systems that have been considered was played by friction.

"... The determination of the actual existence of the regime mentioned entered into the task of the experiment.... In this case, the problem of the structural variety of the particles of ice has no essential significance, but, however, from the experimental standpoint it turned out to be more advantageous to deal with... the snow cover."

Instrumentation consisted of a metal plate 9.5 cm in diameter attached to a spring press. "The moving of the stamp with relationship to its initial installation on the surface of the snow cover was noted by a turn of the drum to which a recording paper had been applied." Diagrams were obtained "representing the dependence between moving of the stamp" (travel) and the stresses acting on the stamp.

"...In these experiments, the rate of motion of the guide screw was varied, and consequently the velocity of the upper (free) end of the spring v_0 . Thus, Group I of the experiments corresponded to a velocity of v_0 of from 0.10 to 0.15 cm/sec, Group II 0.3 cm/sec, and

Group III 0.6 cm/sec.... (Fig. 6).... A series of individual shifts is defined quite clearly on each of the diagrams, during which shifts the elastic energy accumulated by the spring is expended; the force of the compression of the spring at this moment decreases, but, however, the shear that has begun continues to develop, in spite of the fact that the force of compression of the spring has become much less than at the beginning of the shear.

"... We determined the critical load at the beginning of shear. For this purpose, from the diagram we took the ordinates corresponding to the first peak of each of the curves in Fig. 6. The magnitude of the critical load of the beginning of shear was determined by means of dividing the magnitude of the load into the length of the perimeter of the stamp (30 cm). These data are given in Table 2 for all three groups of experiments.

"... In Table 3 we have introduced the values of the function $\varphi(\dot{s})$, taken from the experiment (see Table 2) for zero values of the velocity of shear $\dot{s}$, and for all other values of $\dot{s}$ the magnitudes of the function $\varphi(\dot{s})$ were assumed as equal to one third of $\varphi(0)$ or less....

"With respect to our experiments with the snow cover, we may consider the elastic constant of the spring k = 13.5 kg/cm.... We may determine the mass of the moving parts less accurately, since this mass consisted not only of the mechanical component parts of the experimental installation (stamp, spring, and connecting elements), but also included a certain mass of snow directly under the stamp. In our experiments, the moving mass amounted, on the average, to m = 10 kg.... Substituting the data mentioned into expression (11), we obtain

$$t = \sqrt{\frac{0{,}01}{13{,}5}}\, t_1 = \frac{1}{37}\, t_1.$$

"... The results of the calculations mentioned (using the above equation) are given in Table 3 (lower three lines). The data in Table 3 were also made the basis of the construction of Fig. 4, by means of which the differential equation of motion (12) is solved...."

In another report, Berdennikov (1956) analyzes the mechanism of ice jams using hydraulic principles. He mentions shifting of the ice jam, but does not describe it in more detail then in the previous paper.

"General description of the process of ice jam formation on rivers

"... The general formation process can be divided into the following stages:

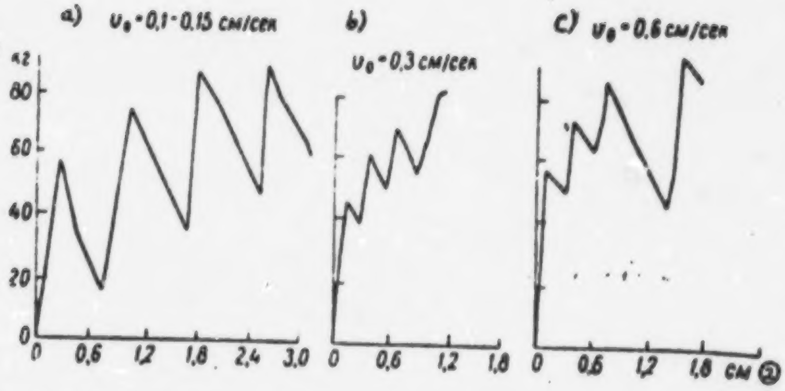


Fig. 6. Curves of vertical movement of stamp in snow cover (cm) as a function of load (kg). a) v_0 = 0.1-0.15 cm/sec; b) v_0 = 0.3 cm/sec; c) v_0 = 0.6 cm/sec. 1) Kilograms; 2) Centimeters. (Berdennikov, 1963)

	Group I	Group II	Group III
Velocity, cm/sec	0,10-0,15	0,3	0,6
Load, kg	30	25	23
Critical magnitude of load at moment of beginning of shear, kg/cm	1,00	0,83	0,77

Table 2. Critical Load of the Beginning of Shear in Experiments with a Stamp for Snow Cover. (Berdennikov, 1963)

TABLE 3

Results of Calculation of the Functions $F(\dot{x})$ and $\frac{1}{k}F\left(\sqrt{\frac{k}{m}}\frac{dx}{dt_1}\right)$ according to Formulas (6) and (14) on the Basis of Data from the Experiments with the Snow Cover (Table 2)

① Функция	② Значения скоростей $\dot{s}$ и $\dot{x}$ (см/сек.)									
	−0,2	−0,1	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7
③ По группе I опытов, $v_0 = 0,1-0,15$ см/сек.										
$-\varphi(\dot{s})$	<0,33	0,33	±1,0	−0,33	<−0,33	—	—	—	—	—
$F(\dot{x})$	>0	>0	0	−0,67 1,33	<0,67	<0,67	—	—	—	—
④ По группе II опытов, $v_0 = 0,3$ см/сек.										
$-\varphi(\dot{s})$	0,28	<0,28	±0,83	−0,28	<−0,28	—	—	—	—	—
$F(\dot{x})$	0	>0	>0	0	<0	−0,55 1,11	0,55	<0,55	—	—
⑤ По группе III опытов, $v_0 = 0,6$ см/сек.										
$-\varphi(\dot{s})$	0,26	<0,26	±0,77	−0,26	<−0,26	—	—	—	—	—
$F(\dot{x})$	0	>0	>0	0	<0	<0	<0	<0	−0,53 1,07	0,53
⑥ Значения скорости dx/dt_1 (см/сек.)										
	−0,0054	−0,0027	0	0,0027	0,0054	0,0081	0,0108	0,0135	0,0162	0,0189
⑦ По группе I опытов, $v_0 = 0,1-0,15$ см/сек.										
$\frac{1}{k}F\left(\sqrt{\frac{k}{m}}\frac{dx}{dt_1}\right)$	<0	<0	0	0,0098 −0,0050	<−0,0050	—	—	—	—	—
⑧ По группе II опытов, $v_0 = 0,3$ см/сек.										
$\frac{1}{k}F\left(\sqrt{\frac{k}{m}}\frac{dx}{dt_1}\right)$	<0	<0	0	>0	>0	0,0082 −0,0011	<−0,0041			
⑨ По группе III опытов, $v_0 = 0,6$ см/сек.										
$\frac{1}{k}F\left(\sqrt{\frac{k}{m}}\frac{dx}{dt_1}\right)$	<0	<0	0	>0	>0	>0	>0	>0	0,0079 −0,0038	<−0,0038

1) Function; 2) Values of velocities $\dot{s}$ and $\dot{x}$ (cm/sec); 3) With respect to group I of the experiment, $v_0 = 0.1-0.15$ cm/sec; 4) With respect to group II of the experiment, $v_0 = 0.3$ cm/sec; 5) With respect to group III of the experiment $v_0 = 0.6$ cm/sec; 6) Values of velocity dx/dt_1 (cm/sec); 7) With respect to group I of the experiment, $v_0 = 0.1-0.15$ cm/sec; 8) With respect to group II of the experiment, $v_0 = 0.3$ cm/sec; 9) With respect to group III of the experiment, $v_0 = 0.6$ cm/sec. (Berdennikov, 1963)

I. Cessation of transitory powers of the frazil and development of fixed frazil ice.

II. Subsurface accumulation of ice materials (frazil, brash ice) due to drift from the open stretch situated upstream.

III. Compaction of the accumulated ice masses, associated with mobility in current direction.

IV. Narrowing of sections of the channel on the observed stretch, following an increase in amount of ice materials, or shifting of these from the wider into the narrower stretches of the channel.

"All of the stages are not always present in jam formation. In rivers, for example, where frazil moves in a suspended state, the II stage will have greatest significance. In rivers where the autumn - winter period has ice drift plus frazil activity, only stage I occurs, and the resultant jams have no great intensity. In rivers where accumulated frazil floats on the surface, ice jam development encompasses stages I & III. The passage of the ice-jam into stage IV indicates its very intense development....

"Quantitative calculations of ice masses contributing to the formation of ice jams

"For qualitative descriptions of the frazil-ice materials utilized in forming ice jams, the predominance of subsurface and anchor ice is most significant.

"In quantitative accounts, however, it is necessary to evaluate the total amount - that carried to the 'ice edge'*, as well as the individual parts - those exhausted in formation of the ice sheet, plus the frazil accumulated beneath the ice. Thus in quantitative calculations of the ice body participating in ice jam formation, both the ice being brought in, and the ice being spent in the region of the 'ice-edge' (kromka), must be taken into account.

"An equation balancing all the ice materials contributing to the jam formation can be written as follows:

$$N - F - M - P = 0 \qquad (1)$$

where,
N - is the amount carried to the 'ice-edge'
F - is the amount used in formation of the frazil ice sheet
M - is the amount of frazil under the ice which, during shifting of the 'ice-edge', accumulated within a given interval

---

*T.N. appears to be the leading edge of the ice cover

P - is that member of the equation which includes the amount of ice melted during positive water temperatures, as well as the amount of ice carried out by the current beyond the limits of the jam area."

"Equation (1) is applicable in situations where the initial ice material moves in the form of slush mats ('carpets', 'wreaths', or 'lumps')* on the surface of the river.

"Now, let us examine each member of equation (1) separately.

"The size of the first member can be arrived at by determining the flow of frazil in the confining 'fold'** situated slightly above the 'ice-edge'. The calculated expression has the following form:

$$N_0 = \alpha B v a \Delta t, \qquad (2)$$

where, N_0 - is the flow of frazil in the 'fold' of observation (m)
α - is that segment of the river surface covered by frazil
B - is the width of the transitory portion of the river in the 'fold' of observation (m)
v - is the average surface current velocity, along the profile (m/sec)
a - is the amount of ice in the frazil accumulation (t/m^2)
Δt - given time interval (sec)."

"The method for determining the amount of frazil dispersed is given in Rymsha (1954).

"Because of the shifting of the 'ice edge' at the margins of the jam area, the 'fold' of observation, for determining the frazil flow, is also shifted. For this reason, the principal 'fold' is chosen above the assumed area of the ice jam and only that amount of frazil is considered, which passes through the 'fold' in transit. In such a case, it is necessary to account for the additional amount of frazil forming in the area between the principal 'fold' and the 'ice edge'. This amount can be calculated according to the heat balance method for open waters. The sum of these two quantities constitutes the total amount of ice brought in to the 'ice edge' (N).

"The amount of material used in the formation of the ice sheet can be determined from the following equation:

$$F = \delta B w h_0 \Delta t, \qquad (3)$$

---

*T.N. "carpets", wreaths", etc. describe slush mats
**T.N. range of observation

where, δ - is the density (weight/volume) of the frazil (t/m^3)
B - is the average width of the river (m), which remained transitory for the movement of (frazil 'carpets') slush mats
w - is the rate of shifting of the 'ice edge' (m/sec)
h_0 - is the initial thickness of the frazil layer (m).

"... The greatest difficulty is encountered in determining the initial thickness of the frazil layer, because this is inaccessible to direct measurements....

"A. M. Yestifeyev (1951) examined the resistance which emerged during cohesive activity due to 'sticky' friction among the frazil particles themselves, or against the shore. The coefficient introduced here - that of frazil viscosity - varies with the air temperature and other meteorological conditions. If the significance of this coefficient were analyzed in controlled laboratory conditions, it would be possible to determine the initial thickness of the frazil layer during the formation of the ice cover, from the air-temperature, the slope of the river, and from the extent and velocity of the current. It must be kept in mind, however, that the application of a solely viscous mechanism for the movement of slush mats, the method used by A. M. Yestifeyev, does not completely correspond to actual conditions. In addition to the viscous frictional forces involved in movement, it is necessary to consider the fundamental stresses and strains. In this regard, Yestifeyev's method needs specification; this is treated below.

"We select an element from the frazil layer during that period when the surface of the river is occupied by mobile slush mats. (Fig. 1). We choose the 2 coordinates, (y) - as the horizontal line representing the center of the river, and (x), its transverse; then we assume

x = the distance from the horizontal line to the element
dx = width of the element
1 = its length (1.0)
h = thickness of the frazil layer.

"If the movement of the slush mats meets resistance, then within the boundaries of the chosen element, the velocity must be changed to dv. The velocity of the slush mats decreases progressively, at certain times approaching zero (i.e. during freeze-up).

"For the period when a balance exists between the resistance of the slush mats and the dynamic forces of the river's current, the following equation holds:

$$h\left(\tau_0 + \eta \frac{dv}{dx}\right) = \frac{1}{2} \gamma i H_0 x. \qquad (4)$$

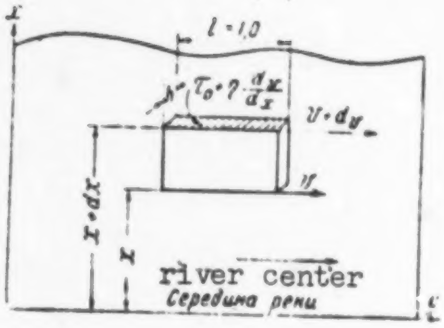

x
$l = 1,0$
$\tau_0 + \eta \frac{dv}{dx}$
$v + dv$
v
$x + dx$
x
river center
Середина реки

DIAGRAM 1
(Berdennikov, 1956)

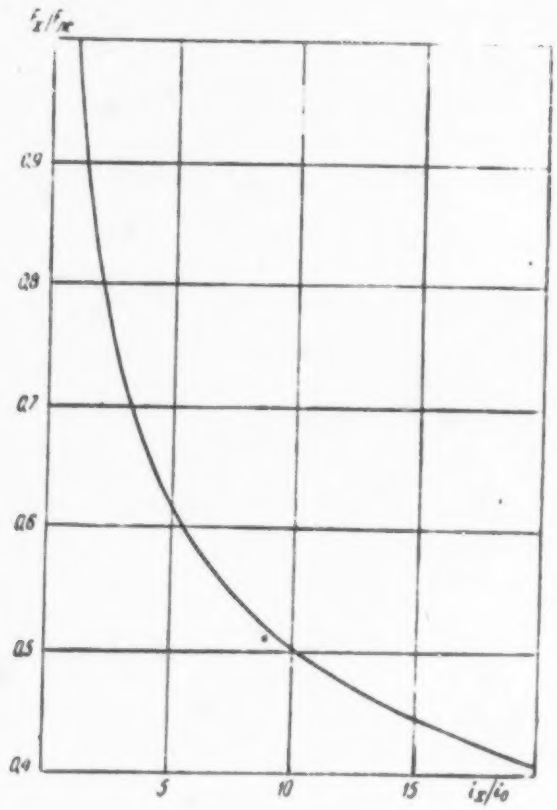


DIAGRAM 2
Narrowing of the channel during an ice jam $F_x / F_{ж}$ in relation to increase of slope $\left(\frac{i_x}{i_0}\right)$.
(Berdennikov, 1956)

where, τ_0 - is the fundamental stress of the frazil layer
η - is the viscosity coefficient
γ - is the specific gravity of water, other things being equal (t/m^3)
i - is the slope of the water surface during freeze-up
$H_{\bullet}$ - thickness of the water layer under the ice, or the average depth of the river, excluding the thickness of the frazil layer.

"In equation (4) it is necessary to consider the thickness of the frazil layer (h) as transitional, in view of the fact that slush mats extend their advance, and due to their cohesive activity, the thickness increases. This phenomena, occuring frequently on rivers, is called ' podvyzhek' (advancement). This advance of the frazil ceases when the thickness reaches certain limits h_0 . When v=o, we add to equation (4):

$$h_0\tau_0 = \frac{1}{4} i H_{\bullet} B. \qquad (5)$$

where, B is the width of the river.

"Let us assume that morphologic and hydraulic conditions on the observed stretch of the river remain unchanged, and therefore the right side of equation (5) stays constant. Then, the thickness of the frazil layer and the magnitude of the fundamental stresses τ_0 will change, their ratio being inversely proportional.... The magnitude of the fundamental stresses τ_0 is increased as the air-temperature is decreased. This is explained by the fact that during greater frosts, the amount of frazil ice materials spent in the formation of an ice cover is smaller, and during mild weather, it is larger. In other words, with colder weather, the slush mats freeze-together easily, adhering predominantly on the surface and bring about greater shifting of the 'ice edge'. In milder weather, where the fundamental splitting stresses, τ_0 , are slight, the initial thickness of the frazil layer, h_0 , is necessarily, in regard to equation (5), larger."

"Let us examine further, the initial equation of balance of ice materials (1), in order to evaluate the remaining members. As mentioned earlier, the role of the P member can be decisive where there is inflow of positive temperatures into the river, or where frazil exists in a suspended state.

"It must be remembered that, in those stretches of a river where an ice cover is present, the current velocity is considerably decreased as compared to that in open waters. Consequently, whenever frazil occurs in a suspended state in open waters, it adheres and accumulates in the area of the leading edge of the ice cover. In the light of such considerations, let us examine, first, the approximate size of P insignificant.

"For calculating the amount of ice material adhering under the ice, while shifting of the leading ice-edge is in process, we rewrite equation (1) as:

$$M = N \quad \delta B w h_0 \Delta t. \tag{6}$$

"In the construction of equation (6) it is shown that during continuous intense ice drift, a more pronounced shifting of the leading ice edge, corresponds to a small amount of ice in the ice jam; and inversely, with decrease in shifting intensity, the amount increases. In such a way, even in early stages of ice jam formations, some objective indexes can be established in regard to the intensity of that process."

"Hydraulic characteristics of ice jams

"In the present work, we will concern ourselves with a given discharge, known from observation. For clarity of conclusions, it is reasonable to assume a constant discharge, keeping in mind that, in reality, it does change, as, for example, in rivers flowing sluggishly out of large lakes. Acceptance of a fixed discharge allows determination of hydraulic conditions both in the presence and absence of ice jams. There are situations where hydraulic conditions during an ice jam, assuming a constant discharge, cannot be compared to conditions of the pre-freezeup period of that same jam year. In most cases, however, such comparisons of hydraulic conditions during ice jams, with those of the pre-freezeup periods, are irrelevant; the reason for this is that, if the discharge does indeed change, in making the comparisons, it is necessary to choose another period without ice, having the appropriate amount of discharge.

"The slope of the river's-surface appears to be a more significant characteristic of hydraulic conditions -- both in ice-jam periods and in pre-freezeup periods. Special emphasis must be placed on the river of a uniform current, in regard to hydraulic conditions. This work, in fact, will be focused on the effect of a uniform current under an ice cover. From the moment of initiation of freezeup, the amount of discharge will be regarded constant; consequently, the slope will remain fairly unchanged during freezeup, lacking substantial ice jams, but will change considerably in freezeups with ice jams.

"The size of the hydraulic radius depends primarily on the morphology of the channel, which, in turn, usually determines the stable characteristics during the period free of ice. For the freeze-up period, the hydraulic radius is equal to half the average height of the water-section flowing underneath the ice. The narrowing of the cross-section of the river during an ice jam, will obviously be expressed by a decrease in size of the hydraulic radius; this makes the hydraulic radius a determining element of the river's flow during the ice jam formation period.

"The relationships between all the hydraulic elements, and their effects on conditions of river-flow beneath an ice cover, were studied by: N. N. Pavlovskii, G. K. Lotter, A. N. Rakhmanov, I. I. Levi, F. I. Bidyn, P. N. Belokon, L. M. Kovalev, and numerous others.

"The basic equation correlating the hydraulic elements of uniform currents flowing beneath an ice cover can be stated as:

$$v_{\text{лс}} = \frac{1}{n_{\text{пр}}} R_{\text{лс}}^{\frac{2}{3}} i_0^{\frac{1}{2}}, \tag{7}$$

where, $v_{\text{лс}}$ - is the current velocity during freeze-up,
$n_{\text{пр}}$ - is the reduced roughness coefficient of the channel and the ice cover,
$R_{\text{лс}}$ - is the hydraulic radius of the stream during freeze-up, without ice jams
i_0 - is the slope of the water surface.

"Equation (7) has wide application in analyses of the winter regime of rivers, however, difficulties arise in determining (choosing) a valid reduced roughness coefficient; it can be determined by the equation:

$$n_{\text{пр}} = \frac{n_0 \Pi_0 + n_{\text{л}} \Pi_{\text{л}}}{\Pi_0 + \Pi_{\text{л}}},$$

where, n_0 and Π_0 - is the roughness coefficient and the wetted perimeter for the channel bed,
$n_{\text{л}}$ and $\Pi_{\text{л}}$ - that for the ice.

"The problem of the roughness coefficient of the river's channel (n_0) has been worked over in considerable detail during recent years. In large rivers and canals, the values of this coefficient vary within a relatively narrow range: from 0.02 in rivers with a fairly 'washed-out' channel and free-flowing current to 0.08 in reaches containing rapids and restricted turbulent currents with a foamy-frothy water surface."

"Thus, we come to the conclusions that the question of the roughness coefficient value of frazil ice must be re-examined in essence, and the overstated value (0.15) attributed to it in Belokon (1938) and Lotter (1932) be rejected.

"The basic expression of relationships between the hydraulic elements of a uniform current (7), is also valid for open water,... however, the values of the roughness coefficient and the hydraulic radius, are only secondary. The following equation is derived:

$$\left(\frac{R_{\text{зс}}}{R_0}\right)^{\frac{5}{3}} = \frac{n_{\text{пр}}}{2n_0} \qquad \text{where} \qquad \frac{Q_{\text{зс}}}{B_{\text{зс}}} = \frac{Q_0}{B_0};\ i_{\text{зс}} = i_0. \qquad (8)$$

where, '0' represents the period free of ice, and ' зс ', the freeze-up period.

"Table 1 contains the reduced quantities $\frac{R_{\text{зс}}}{R_0}$ for different values of $\frac{n_{\text{пр}}}{n_0}$ in equation (8).

"From hydrometric studies of a great number of large rivers... it can be confirmed that the current velocity following freeze-up, compared to the velocity of an open stream with the same discharge, decreases not more than 50%, usually within 20-40%. Keeping in mind the ascribed constancy of a given discharge, the modifications of the current velocity within a certain range can be referred to the calculated modifications of the hydraulic radius during freezeup ($R_{\text{зс}}$) as related to its value in the absence of ice (R_0). We derive the following equation:

$$0{,}6 < \frac{R_{\text{зс}}}{R_0} < 0{,}7 \qquad \text{where} \qquad \frac{Q_{\text{зс}}}{B_{\text{зс}}} = \frac{Q_0}{B_0}. \qquad (9)$$

"From the comparisons in Table 1 we conclude that the variations of the value for $\frac{R_{\text{зс}}}{R_0}$ within the indicated limits (9), are in accordance with the variations of $\frac{n_{\text{пр}}}{n_0}$ in the range between 0.87 to 1.12.

"For this reason, in the case of frazil-carrying rivers, for many hydraulic calculations, the first approximation can be considered

$$\frac{n_{\text{пр}}}{n_0} = 1{,}0. \quad "$$

"Let us examine the... simplified scheme of ice jams under conditions of steady flow. In this elementary situation, the value of the sought-after characteristic can be obtained from the following ratio:

$$\frac{Q}{\sqrt{i}} = K. \qquad (10)$$

$\frac{r_{np}}{r_0}$	0.75	0.87	1.00	1.12
$\frac{R_{nc}}{R_0}$	0.556	0.608	0.660	0.707

$\frac{r_{np}}{r_0}$	1.25	1.37	1.50	2.00	2.5
$\frac{R_{nc}}{R_0}$	0.754	0.798	0.841	1.000	1.15

TABLE 1 Correlation of significance of the hydraulic radius in equation (8) (Berdennikov, 1956)

where, Q - is the discharge (m^3 /sec)
i - is the slope of the water surface
K - is the 'water-transmissivity' (m^3 /sec).

"Using equation (10), we can examine the changes in hydraulic conditions which occur in the time from the pre-freezeup period to the freezeup accompanied by ice jams. Evidence indicates that the transmissivity during ice jams is smaller compared to the pre-freezeup period or the period of freezeup without jamming. Consequently, the slope of the jammed stretches can be expected to be greater.

"The principal hydraulic conditions for the ice jam period can be expressed as:

$$\sqrt{\frac{i_x}{i_0}} = \frac{K_0}{K_x} > 1.0 \qquad \text{when} \qquad Q_x = Q_0. \qquad (11)$$

where, 'o' refers to the ice-free period
and 'x' to the ice jam period.

"Using the expressed relationship between the hydraulic elements during pre-freezeup conditions and the ice jam period, equation (11) can be written as follows:

$$\sqrt{\frac{i_x}{i_0}} = \frac{n_{np}}{2n_0}\left(\frac{R_0}{R_x}\right)^{\frac{5}{3}} \qquad \text{when} \qquad \frac{Q_{xc}}{B_{xc}} = \frac{Q_0}{B_0}. \qquad (12)$$

"... A more straight forward calculated expression is derived, solving the last equation in conjunction with equation (8). When we substitute the value of the hydraulic radius by a, proportional to it, area of the water section, we derive:

$$\frac{F_x}{F_{xc}} = \left(\frac{i_x}{i_0}\right)^{-0.3} \qquad \text{when} \qquad n_{np} \geq n_0. \qquad (13)$$

"Equation (13) states the relationship between the slope increase in the ice jam stretch and the narrowing of the channel (see diagram 2).

"For the ice jammed stretch of the river, calculation of the water-transmissivity is determined from equation (10), into which enter the slope and discharge, as well as expression of other supporting hydraulic elements of the river current having steady flow. Thus, we derive the equation for this water-transmissivity:

$$K_s = \frac{2B_s}{n_{\text{пр}} R_s^{\frac{5}{3}}}. \qquad (14)$$

"In this equation, an important place is occupied by the hydraulic radius, the width of the river, and the reduced roughness coefficient for the given stretch of the river. This equation is valid for hydraulic elements involved in ice jam in the presence of a steady flow current. However, in conditions of unsteady or unestablished flow, the calculations become more complex. In such cases, the principal indicator of jam formation in a given stretch of the river, is the increase of water surface slope, as compared to the slope of that stretch during the pre-freezeup period, or during the period of freeze-up without an ice jam.

"The slope increase during an ice jam results in a modification of the longitudinal profile, which, in turn, is expressed by a rise of the water horizon in the jam stretch.

"Let us examine a stretch of a river in which the lower end is already occupied by an ice jam, and the upper end is still free from ice. In the jammed section there is a high rise in water level. Consequently, in accordance with the proximity to the jam, in the upper-lying end a support will be formed and will be evidenced in the progressive transition of the water-level from its normal state, (pre-freeze up) to a higher one (during the jam).

"With the development of ice jam phenomena in various parts of the river, the boundaries of the jam move upstream and the area of the supports shifts accordingly. It is essential to note that the expansion of this support with time, habitually precedes the development of ice jam phenomena, and, therefore, can serve as an anticipating signal of the approximate starting time of jam development. It follows then, that in order to predict the time of jam formation, it is necessary to study the support phenomena on the observed stretch of the river.

"For the area of support, the following expression is valid, showing the relationship between hydraulic elements during unsteady flow:

$$i = \frac{v^2 n^2}{R^{\frac{4}{3}}} + \alpha \frac{d}{dS}\left(\frac{v^2}{2g}\right). \qquad (15)$$

where, dS - increase in length of the stretch in the direction of the current
d - is the coefficient indicating the degree of irregularity of flow."

"In working out the problem of the geometric characteristics of the channel, and the conditions of unsteady flow, let us examine the significance of the position of both in the 'invarient modulation of resistance.' A solution to equation (15) is possible if the following functions are used:

$$\Omega = \omega(H); \quad B = b(H); \quad F_m = \frac{\Delta}{Q^2} = f(z). \qquad (16)$$

where, $\omega(H)$ - is the area of the water section dependent on the depth of the filled channel
$b(H)$ - is the width of that stretch
F_m - is the resistance modulation
Δ - is the degree of drop of the water surface in the observed stretch
$f(z)$ - is the functional dependence on the level rise -

"Further investigation deals with separate hydraulic phenomena of an unestablished flow, which frequently plays a major part in the ice jam period. When the formation of a jam plug occurs in a short time interval, and the river's flow has a relatively large velocity, supplemented by a lot of stored kinetic energy, the movement becomes one of long waves of support or long waves of filling. The rise of such waves frequently has a decisive influence on the achievement of the peak level during ice jam construction.

"Relationships between hydraulic elements in an unestablished flow can be stated as:

$$i - \frac{\partial H}{\partial S} = \frac{1}{g}\frac{\partial v}{\partial t} + \frac{v}{g}\frac{\partial v}{\partial S} + \frac{Q^2}{K_s^2}. \qquad (17)$$

where, dt - is the time increase
Q - is the discharge."

"Let us notice that execution of practical calculations for an unestablished flow necessitates the study of morphologic data of the river channel, in which more attention must be given to the accumulating capabilities of the channel.

"In supplement, let us consider the characteristics of a practical sphere of application of equations (7)-(17).... If during the freeze-up period of the frazil-carrying rivers, observations showed a slope increase on a stretch having a steady flow, this would indicate a narrowing of the channel due to the frazil accumulating under the ice in that stretch. Thus, through observations of level changes, the crowning stage of jam formation is revealed.

"For an evaluation of the degree of channel restriction during the ice jam, we can use equation (13), which shows that even with the smallest value of the argument $\frac{i_x}{i_0} = 1$, the degree of channel narrowing is also expressed by the unit ($\frac{F_x}{F_{\text{лс}}} = 1$), which corresponds to a jam-free freezeup. With an extreme value of that argument, that is, an infinite increase of $\frac{i_x}{i_0}$ the proportion $\frac{F_x}{F_{\text{лс}}}$ approaches zero. In this manner, on the basis of equation (13), we arrive at the hydraulic characteristics of ice jams through the calculation of data on slopes.

"It is not necessary to treat separately the relationship between the ratio $F_x / F_{\text{лс}} < 1$, as expressed in equation (13), and that of the water-transmissivity of a jammed stretch. If for a given stretch, the degree of narrowing of the channel $F_x / F_{\text{лс}} < 1$, we can conclude that there, the water-transmissivity in that stretch also becomes smaller than its original value.

"Now, we can proceed from the evaluation of ice jam phenomena, to the calculation of their dimensions according to hydraulic elements. This can be done by two methods, to be discussed below.

"According to the general description of the jam formation process, during the initial stage of that process, the river mirror of the observed stretch is covered with an immobile layer of frazil. This stage is characterized by a corresponding area of the water section $F_{\text{лс}}$, with which, by means of equation (13), we can compute the area of the water section of a stream during an ice jam. The expedient quantity of $F_{\text{лс}}$, in some cases, can be derived from data on freezeup without jams observed throughout a number of years.

"On the other hand, we can arrange data on the water-transmissivity of the jammed section, and by substituting it into equation (14) we can compute the size of the hydraulic radius of the stream during the jams (R_x):

$$h_{\text{погр}} = H_0 + \Delta H_x - 2R_x, \qquad (18)$$

where, $h_{\text{погр}}$ - is the amount of immersed frazil and ice
H_0 - is the average depth of the observed stretch for a stipulated water horizon
ΔH_x - is the rise of water level above the stipulated horizon during the ice jam.

"For a final calculation of the thickness of the frazil and ice layer in the jam, we use the floating conditions of the frazil and ice:

$$h_{\text{ш}} = 1{,}09\ h_{\text{напр}} \qquad (19)$$

where, $h_{\text{ш}}$ - is the thickness of the frazil ice in the jam.

"Thus through the use of reduced equations, supplemented by data from observations of ice jam phenomena, it is possible to determine the essential hydraulic characteristics of ice jams: degree of channel narrowing, the water-transmissivity, the dimensions of the jam, and its strength.

"Analysis of conditions of ice jam development

"Let us examine the exact conditions of an ice jam stretch on a large frazil-carrying river where intense ice jams are common.

"A general representation of ice jam development of that river is given in the diagram of the longitudinal profile, for three successive terms, each having an interval of several days (diagram 3).

"In the first period, that is, at the very beginning of the IV stage of jam formation, an even rise in water level takes place; later, in accordance with the jam development (2nd & 3rd periods), the increase in water level rise occurs more sharply. For comparison, the profile of the water surface for the period free of ice is included.

"The water horizons during the jams, illustrated in diagram 3, do not appear instantaneously as distinct profiles; on the contrary, the state of the river's current remains unchanged for considerable periods, at times as long as a few months.

"The area of the river having the extreme increase in slope of water surface with a narrowing of the water section in the channel during jam formation, does not always remain in place, but, as a rule, is shifted in the direction opposite the current movement. On the studied river, as well as on many other rivers, the shifting of the jam area along the length of the river, is closely related to the shifting of the leading ice edge. This serves us as a basis for examining the ice jam formation process in reference to the covering of the river's 'mirror' by a stationary layer of frazil ice in stage I of that process. In diagram 3, it is shown that the jam area shifts along with the shifting of the leading ice edge."

"For a concise hydrographic characterization of the observed stretch, diagram 4 supplies information about its width and average depth, referring to the calculated or conditional water horizon.

"Special interest is provided by data on the sustenance of the ice material in the form of slush mats during the frazil drift. The figures

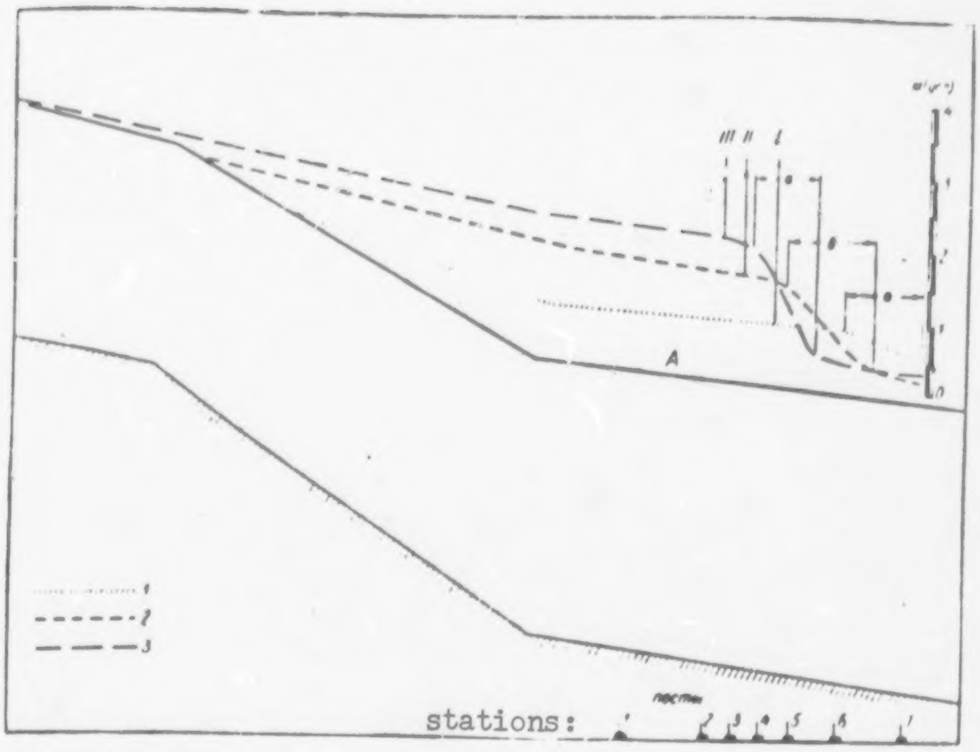


DIAGRAM 3

Schematic longitudinal profile of the river surface for the period free from ice (A) and for distinct terms of the fourth stage of jam development. (Berdennikov, 1956)

1 - position of the ice edge during state I
2 - position of the ice edge during state II
3 - position of the ice edge during state III
    a - ice jam zone during ice edge position I
    б - ice jam zone during ice edge position II
    B - ice jam zone during ice edge position III.

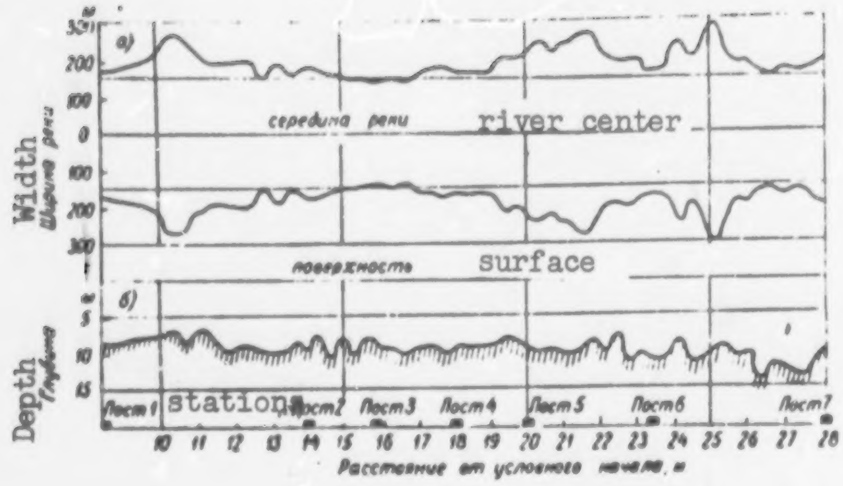
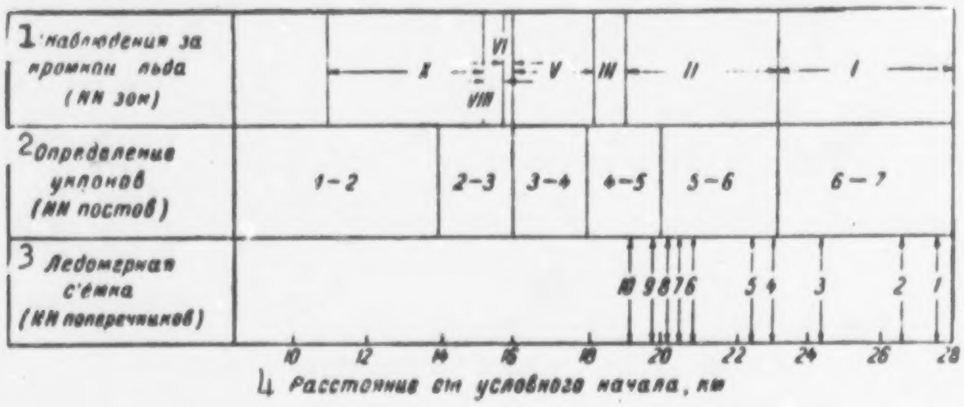


DIAGRAM 4 The width (a) and the average depth (б) of the river on the jammed stretch. (Berdennikov, 1956)



1 наблюдения за кромкой льда (NN зон)
X
VIII
VI
V
IV
II
I
2 Определение уклонов (NN постов)
1-2
2-3
3-4
4-5
5-6
6-7
3 Ледомерная съемка (NN поперечников)
10 9 8 7 6
5 4
3
2
1
10 12 14 16 18 20 22 24 26 28
4 Расстояние от условного начала, км

DIAGRAM 5 Zone of individual observations of jam phenomena. (Berdennikov, 1956)

1 observations of ice edge (NN zones)
2 determination of slopes (NN stations)
3 ice-measuring survey (NN transverses)
4 distance from point of origin, in km.

in Table 2 are the results of a series of measurements which can be considered fairly representative of a first approximation.

"On the basis of equation (2), we calculate the approximate amount of ice material which is brought in from the leading ice edge, by the frazil drift. Throughout the years, the total mass of frazil varies within an extremely wide range, expressed principally in calculation with variable values of a and Δl .

"For qualitative examples of all the following calculations, we choose a year in which the indicated components of equation (2) had fairly high values. For the calculated period, the frazil covering the surface (visual determination) consisted of a series of folds about 2-4 km. apart. In view of the fact that folds of observation were found in similar conditions, it is expedient to introduce into the calculations, the coordinated results of all the observations in order to exclude any subjective errors in the observations. Checking computations of the heat balance showed that the additional amounts of frazil forming between the observation folds were insignificant. Table 3 shows the resultant calculations of the frazil flow, after equation (2), which can be accepted as daily amounts of frazil brought in to the ice edge during the autumn-winter period of the jam year....

"Let us turn to the ice jam phenomena existing between December 12 and January 2. We will use as a basis, here, the data on ice edge shifts, regime of water-level and slope, and data supplied by ice-measuring surveys.

"The indicated data refers to the ice jam stretch illustrated in diagram 3. For purposes of orientation, we assumed the entrance of one of the tributaries to be the point of origin, and calculated distances in the direction of the current. Diagram 5 illustrates the areas of various views of observation and the distances from the assumed point of origin.

"In agreement with the designations of ice jam phenomena in the present work, the initial stage of formation appears to be the covering of the river surface by a stationary layer of frazil; in relation to this, our primary interest concerns the data on the shifting of the leading ice edge within the observed stretch.

"Generally, this shifting movement occurs in an upstream direction, however, at certain times, following the movement of frazil masses, a regular shifting ceases completely, or changes direction. Thus, the periods of regular shifting of the ice edge, alternate with periods when the ice edge 'pulsates'.

"In diagram 6, the inclined segments of the line designate the periods of regular shifting of the ice edge, while the horizontal (broken) lines represent the 'pulsating' periods. Calculations of the interval indicating the rate of advancement of the ice edge, in diagram 6, were based on the

1 № пробы	1	2	3	4	5	6	7	8	9	10	11	12	13	14
2 Количество льда, т/м²	0,18	0,07	0,07	0,07	0,07	0,18	0,20	0,15	0,14	0,06	0,20	0,16	0,16	0,14

3 Средн. 0,132 т/м²

TABLE 2 Ice content in slush mats. (Berdennikov, 1956)

1 no. of sample
2 amount of ice, t/m^2
3 average. 0.132 t/m^2.

1 Дата	2 Данные визуальных наблюдений за покрытием шугой зеркала реки в различных пунктах (в днях)						3 Принятое к расчету значение x	4 N_0 т/сут.	5 Примечание
	пост № 1	пост № 2	пост № 3	пост № 4	пост № 5	пост № 6			
16/XII	0,25	0,25	0,50	0,50	0,25	0,50	0,25	$0{,}92 \cdot 10^6$	$a = 0{,}132$ т/м² $v = 0{,}95$ м/сек. $B = 340$ м $\Delta t = 86\,400$ сек. $\sum N_0 \cong 24 \cdot 10^6$ т.
17/XII	0,50	0,25	0,50	0,50	0,50	Ледостав	0,50	$1{,}85 \cdot 10^6$	
18/XII	0,50	0,50	0,50	0,50	0,50		0,50	$1{,}85 \cdot 10^6$	
19/XII	0,50	0,50	0,50	0,50	0,50		0,50	$1{,}85 \cdot 10^6$	
20/XII	0,50	0,50	0,25	0,50	Ледостав		0,50	$1{,}85 \cdot 10^6$	
21/XII	0,50	0,50	0,50	0,50			0,50	$1{,}85 \cdot 10^6$	
22/XII	0,50	0,50	0,50	Ледостав			0,50	$1{,}85 \cdot 10^6$	
23/XII	0,50	0,50	Ледостав				0,50	$1{,}85 \cdot 10^6$	
24/XII	0,50	0,50					0,50	$1{,}85 \cdot 10^6$	
25/XII	0,25	0,25					0,25	$0{,}92 \cdot 10^6$	
26/XII	0,25	0,25					0,25	$0{,}92 \cdot 10^6$	
27/XII	0,25	0,25					0,25	$0{,}92 \cdot 10^6$	
28/XII	0,25	0,25					0,25	$0{,}92 \cdot 10^6$	
29/XII	0,25	0,25					0,25	$0{,}92 \cdot 10^6$	
30/XII	0,25	Ледостав					0,25	$0{,}92 \cdot 10^6$	
31/XII	0,25						0,25	$0{,}92 \cdot 10^6$	
1/I	0,25						0,25	$0{,}92 \cdot 10^6$	
2/I	0,50						0,50	$1{,}85 \cdot 10^6$	
3/I	Ледостав								

TABLE 3 Amount of frazil (N_o) brought in to the leading ice edge during jam formation (calculated by equation (2)). (Berdennikov, 1956)

1 date
2 data from visual observations of ice covering the river surface in specific places
3 accepted value of x from calculations
4 N_o t/day
5 Note.

extent of the route and the length of the interval between the folds of observation. The course of shifting is also shown in diagram 5; here, the numbers of the various segments on the diagram correspond to the numbers on the time intervals in diagram 6. Because during intervals IV, VII, and IX, the ice edge 'pulsated' and did not shift upstream, the corresponding segments were not included in diagram 5.

"As a supplement to data taken from observations of the ice edge shifting, we include information on the meteorological elements which entered into the shifting process (Table 4).

"We proceed to examine stages II and III of the ice jam formation. First, we compute by means of equation (3), the amount of ice lost to the ice cover in the various, separate zones. In compliance with data from the Hydrological Institute, we accept the specific gravity of frazil to be 0.58 t/m^3. Since, the initial thickness of the frazil layer, h_0, formed in the early part of the jam development, is excluded - we use data from the years of freezeup without ice jams.

"Alt[illegible]h measurements of thicknessess of the frazil cover were made 10-20 days [illegible]ter the start of freezeup, they are valid. This is verified by the following: the current velocity from the start of freezeup is sharply decreased and the impact of the flow on the frazil cover is significantly reduced; in addition to this, the frazil masses now freezing rapidly, produce a fixed layer of ice which gradually grows....

"On the basis of study and analysis of various data on the frazil cover thickness, we conclude that the value of h_0 can tentatively be accepted as 0.5.

"Results of calculations of the ice materials lost to the ice-cover formation are given in Table 5. For comparison purposes, the value of N_0 is stated, computed by equation (2), assuming Δt to be the duration of the given time intervals; all the other data is taken from Table 3.

"Table 5 gives the differences between N_0-F, which, according to equation (1), account for the amounts of ice brought in under the ice-cover. From Table 5 it is possible to determine the stage of the ice jam formation in the observed stretch (more precisely, the area of the ice edge shifting). Thus, for the first time interval (17/XII from 0-00 to 6-30), in the stream where the ice edge shifted at a fast rate, all the frazil brought in by the current was used up in the formation of an ice cover and was not brought in under the ice; consequently, for the indicated term, in that particular area only stage I of the jam development occured.

"In the subsequent intervals, although the flow of frazil was the same as on 17/XII, the shifting of the ice edge slackened, the corresponding amount of ice, given-up in the ice cover formation decreased, and a large amount of frazil was brought in under the ice; this was considered a later stage of ice jam development. During the intervals when the ice edge shifted regularly upstream, the second stage of jam development

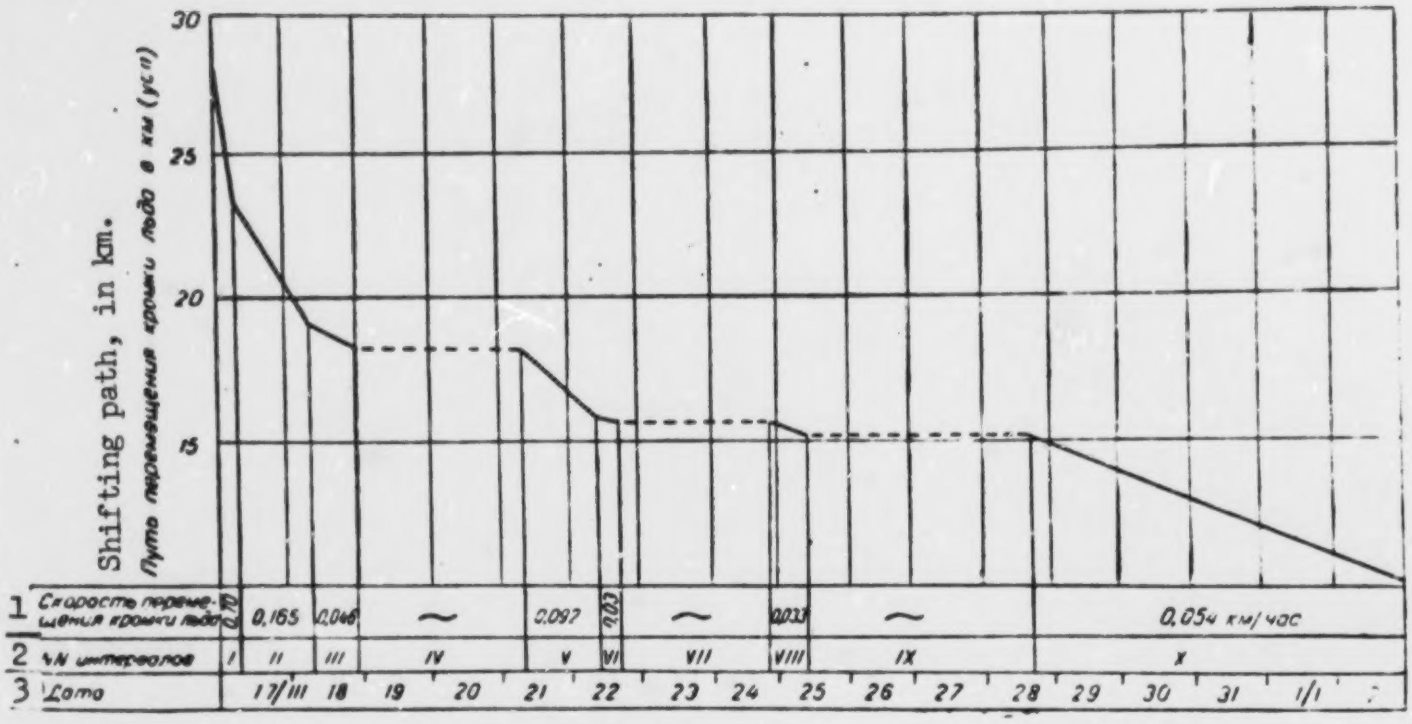


DIAGRAM 6 Shifting of the leading ice edge. (Berdennikov, 1956)

1 Speed of ice edge shifting, in km/hr.
2 NN intervals
3 Date.

1 Дата	16 XII	17 XII	18 XII	19 XII	20 XII	21 XII	22 XII	23 XII	24 XII	25 XII	26 XII	27 XII	28 XII	29 XII	30 XII	31 XII
2 Температура, град.	−6,1	−5,4	−4,8	−5,5	−7,9	−9,6	−9,4	−13,4	−11,0	−4,3	−3,5	−3,4	−5,0	−5,7	6,6	−8,2

TABLE 4 Average daily air-temperature during the jam formation period. (Berdennikov, 1956)

1 Date
2 Temperature, in degrees.

1 № интервала	2 Границы расчетных зон, км (усл.)	3 Приращение площади, $B w \Delta t$, м²	4 По формуле (3) F, т	5 Продолжительность интервала Δt, час.	6 Сток шуги по формуле (2) N_0, т	7 Количество шуги, заносимой под лед, $N_0 - F$, т	8 Стадия формирования зажора
I	27,8—23,2	$1{,}75 \cdot 10^{6}$	$0{,}51 \cdot 10^{6}$	6,5	$0{,}50 \cdot 10^{6}$	0	I
II	23,2—19,0	$1{,}90 \cdot 10^{6}$	$0{,}55 \cdot 10^{6}$	25,5	$1{,}29 \cdot 10^{6}$	$0{,}74 \cdot 10^{6}$	II
III	19,0—18,3	$0{,}25 \cdot 10^{6}$	$0{,}07 \cdot 10^{6}$	15,0	$1{,}16 \cdot 10^{6}$	$1{,}09 \cdot 10^{6}$	II
IV	18,3—18,3	0	0	57,0	$4{,}60 \cdot 10^{6}$	$4{,}60 \cdot 10^{6}$	III
V	18,3—15,9	$0{,}77 \cdot 10^{6}$	$0{,}22 \cdot 10^{6}$	27,0	$2{,}09 \cdot 10^{6}$	$1{,}87 \cdot 10^{6}$	II
VI	15,9—15,7	$0{,}07 \cdot 10^{6}$	$0{,}02 \cdot 10^{6}$	6,0	$0{,}46 \cdot 10^{6}$	$0{,}44 \cdot 10^{6}$	II
VII	15,7—15,7	0	0	53,0	$4{,}10 \cdot 10^{6}$	$4{,}10 \cdot 10^{6}$	III
VIII	15,7—15,3	$0{,}14 \cdot 10^{6}$	$0{,}04 \cdot 10^{6}$	12,0	$0{,}46 \cdot 10^{6}$	$0{,}32 \cdot 10^{6}$	II
IX	15,3—15,3	0	0	78,0	$3{,}00 \cdot 10^{6}$	$3{,}00 \cdot 10^{6}$	III
X	15,3—1[illegible],5	$1{,}45 \cdot 10^{6}$	$0{,}42 \cdot 10^{6}$	128,0	$6{,}60 \cdot 10^{6}$	$5{,}15 \cdot 10^{6}$	II

TABLE 5 Amount of frazil carried under the ice. (Berdennikov, 1956)

1 No. of interval
2 Limits of observed zone (km.)
3 Increase of area, $B w \Delta t$ (m²)
4 After equation (3) F (t)
5 Length of interval Δt (hours)
6 Flow of frazil, after equation (2) N_o, (t)
7 Amount of frazil, carried under the ice, N_o-F (t)
8 Jam development stage

*Note: The amount carried under the ice, in accordance with equation (1) is equal to N - F where $N = N_o + N_s$ and N_s is the amount of frazil observed on the stretch between the principal fold of observation and the ice edge, during heat loss. For the observed period (17/XII - 2/I), heat loss was insignificant, thus N_s was accepted as zero.

materialized that is, the accumulation of ice masses under the ice cover. The frazil brought in under the ice at this time was carried in the channel by means of the shifting ice edge, and the jam-zone expanded lengthwise. It is possible that some of the frazil stranded into the lower stretch where, previously, no frazil existed.

"The time intervals, during which the ice edge pulsated, must be treated separately. During this time, a greater quantity of frazil was brought in under the ice, which was not dispersed by the shifting ice edge. Here, it was not possible to prevent compaction of the frazil accumulations. These intervals, then represent the III stage of jam development."

"Table 6 contains data on the jam formation in the river for the period from 17/XII to 2/I; it includes the slope of the water surface (i); the ratio i/i_0; the degree of channel narrowing ($F_л/F_{нс}$) computed by equation (13); and the water-transmissivity in the jam, calculated by means of equation (10).

"The discharge of the river for the studied period was established as 1540 m^3/sec with less than 10% deviation in either direction.

"The slope, during the period when the ice edge was approaching the boundaries of the observed stretch, decreased. Following the formation of the ice cover, the slope, as a rule, was approximately the same as during the initial period free of ice (i_0).... In the final period, where the jam development passes into stage IV, the slope increases in accordance with the channel constriction ($\frac{F_л}{F_{нс}} < 1$), and with the decrease of the water-transmissivity.

"The narrowing of the channel, following the jam formation, occured first between stations 6 & 7 and on 20/XII in 20 hours $F_л/F_{нс} = 0.69$. Later, the degree of narrowing in that stretch decreased; in the higher situated stretch (between stations 5 & 6), the degree of constriction on 23/XII in 7 hours amounted to 0.48. During the remaining period, until 30/XII inclusive, the proportion $\frac{F_л}{F_0}$ in that stretch varied between 0.62 and 0.49; following the break-down of the ice jam, the water section began to expand. In the stretch between station 4 & 5, channel constriction occured later than in the lower-lying stretches, and in 20 hours or 27/XII, reached the maximum for that year (0.44). In the stretch between stations 3 & 4, the constriction was less significant (on 2/I in 14 hours, equal to 0.62).

"Let us compare the degree of channel constriction during the jam with the distinct ice conditions existing at that time.

"An appreciable amount of pulsating of the ice edge occured in three separate time intervals (Diagram 6. IV, VII and IX). As shown by calculation from equation (1), at this time, a large amount of frazil was brought in under the ice (Table 5).

TABLE 6

(Berdennikov, 1956)

Таблица 6

Гидравлические характеристики зажора

1 Дата	2 Время, часы	3 Участок между постами № 3 и 4 (15,8—18,0 км от условного начала)				4 Участок между постами № 4 и 5 (18,0—19,9 км от условного начала)				5 Участок между постами № 5 и 6 (19,9—23,2 км от условного начала)				6 Участок между постами № 6 и 7 (23,2—27,8 км от условного начала)			
		i_x, ‰	$\frac{i_x}{i_0}$	$\frac{F_x}{F_0}$	K, м³ сек.	i_x, ‰	$\frac{i_x}{i_0}$	$\frac{F_x}{F_0}$	K, м³ сек.	i_x, ‰	$\frac{i_x}{i_0}$	$\frac{F_x}{F_0}$	K, м³ сек.	i_x, ‰	$\frac{i_x}{i_0}$	$\frac{F_x}{F_0}$	K, м³ сек.
7 Начальное значение для периода без льда		0,045	—	—	$22,0 \cdot 10^4$	0,037	—	—	$25,7 \cdot 10^4$	0,033	—	—	$26,8 \cdot 10^4$	0,024			$30,8 \cdot 10^4$
17/XII	00	—	—	—	—	—	—	—	—	0,020	—	—	—	0,024	1,00	1,00	$30,8 \cdot 10^4$
	08	—	—	—	—	—	—	—	—	—	—	—	—	0,028	1,17	0,95	$29,1 \cdot 10^4$
	20	—	—	—	—	0,032	—	—	—	—	—	—	—				
18/XII	20	—	—		—	0,037	1,00	1,00	$25,7 \cdot 10^4$	0,033	1,00	1,00	$26,8 \cdot 10^4$				
20/XII	08		—	—		—	—	—	—	—	—	—	—	0,067	2,79	0,73	$18,7 \cdot 10^4$
	20	—	—	—	—	—	—	—	—	0,285	8,65	0,52	$9,6 \cdot 10^4$	0,057	2,38	0,69	$20,3 \cdot 10^4$
21/XII	08	0,023	—	—	—	—	—	—	—	0,242	7,36	0,55	$9,9 \cdot 10^4$	0,052	2,16	0,79	$21,7 \cdot 10^4$
	20	—	—	—	—	—		—	—	0,234	7,10	0,55	$9,9 \cdot 10^4$	0,052	2,16	0,79	$21,7 \cdot 10^4$
22/XII	08	—	—	—	—	—	—	—	—	0,197	5,97	0,58	$11,0 \cdot 10^4$	0,050	2,08	0,80	$22,0 \cdot 10^4$
	20	—	—	—	—	—	—	—	—	0,200	6,06	0,57	$11,0 \cdot 10^4$	0,039	1,62	0,86	$21,5 \cdot 10^4$
23/XII	07	0,045	1,00	1,00	$22,0 \cdot 10^4$	0,152	4,10	0,65	$12,5 \cdot 10^4$	0,376	11,40	0,48	$7,9 \cdot 10^4$	0,041	1,71	0,84	$21,2 \cdot 10^4$
	20	—	—	—	—	0,226	6,11	0,68	$11,3 \cdot 10^4$	0,360	10,90	0,49	$8,1 \cdot 10^4$	0,043	1,79	0,83	[illegible]
	22	0,045	1,00	0,98	$22,0 \cdot 10^4$	—	—	—	—		—						
24/XII	06	0,114	2,54	0,75	$14,4 \cdot 10^4$	0,226	6,11	0,68	$10,3 \cdot 10^4$	0,320	9,70	0,51	$8,6 \cdot 10^4$	0,041	1,71	0,84	$24,2 \cdot 10^4$
	20	0,114	2,54	0,75	$14,4 \cdot 10^4$	0,342	9,25	0,51	$8,6 \cdot 10^4$	0,255	7,72	0,54	$9,7 \cdot 10^4$	0,046	1,91	0,81	

TABLE 6 cont'd

(Berdennikov, 1956)

25/XII	08	0,190	4,23	0,65	11,0·10^4	0,268	7,25	0,55	9,5·10^4	0,243	7,38	0,55	9,8·10^4	0,033	1,47	0,80	26,5·10^4
	20	0,185	4,11	0,65	11,1·10^4	0,268	7,25	0,55	9,5·10^4	0,240	7,28	0,55	9,9·10^4	0,043	1,79	0,83	23,7·10^4
26/XII	08	0,182	4,05	0,66	11,4 10^4	0,252	6,80	0,56	9,6·10^4	0,220	6,68	0,56	10,2·10^4	0,035	1,46	0,89	26,1·10^4
	20	0,173	3,85	0,66	11,8·10^4	0,290	7,84	0,54	9,1·10^4	0,227	6,90	0,56	10,3·10^4	0,048	2,00	0,81	22,3·10^4
27/XII	08	0,168	3,74	0,67	11,8·10^4	0,231	6,25	0,58	10,0·10^4	0,220	6,68	0,56	10,2·10^4	0,041	1,71	0,84	24,2·10^4
	20	0,155	3,45	0,69	12,7·10^4	0,580	15,65	0,44	6,4·10^4	0,173	5,25	0,61	11,8·10^4	0,030	1,25	0,93	28,3·10^4
28/XII	06	0,182	4,05	0,66	11,4·10^4	0,405	10,95	0,49	7,7·10^4	0,260	7,88	0,54	9,6·10^4	0,037	1,54	0,87	25,5·10^4
	18	0,200	4,45	0,64	11,0·10^4	0,379	10,23	0,50	8,1·10^4	0,180	5,45	0,60	11,8·10^4	0,065	2,70	0,74	19,2·10^4
	22	0,136	3,03	0,71	13,2·10^4	0,453	12,20	0,47	7,2·10^4	—	—	—	—				
29/XII	06	0,123	2,74	0,74	14,0·10^4	0,430	11,60	0,48	7,5·10^4	0,212	6,44	0,57	10,4·10^4	0,046	1,92	0,82	
	18	0,150	3,34	0,69	12,8·10^4	0,410	11,05	0,49	7,6·10^4	0,185	5,60	0,59	11,7·10^4	0,076	3,17	0,71	17,7·10^4
30/XII	06	0,141	3,14	0,71	12,8·10^4	0,390	10,55	0,49	7,9·10^4	0,160	4,85	0,62	11,9·10^4	0,063	2,62	0,75	19,2·10^4
	18	0,127	2,93	0,72	14,0·10^4	—	—	—	—	0,345	10,45	0,49	8,3·10^4	0,080	3,34	0,69	17,2·10^4
31/XII	06	0,150	3,34	0,69	12,8·10^4	0,315	8,50	0,58	8,7 10^4	0,214	6,50	0,57	10,5·10^4	—	—	—	
	18	0,155	3,45	0,69	12,7·10^4	0,295	7,97	0,59	9,0·10^4	0,173	5,25	0,61	11,7·10^4	0,067	2,79	0,73	18,4·10^4
1/1	06	0,204	4,56	0,63	11,0·10^4												
	18	0,168	3,76	0,67	11,8·10^4												
2/1	06	0,173	3,55	0,66	11,8·10^4												
	14	0,205	4,56	0,62	11,0·10^4												
	22	0,132	2,94	0,72	13,2·10^4												

TABLE 6 Hydraulic characteristics of the jam. (Berdennikov, 1956)

1 Date
2 Time, in hours
3 Stretch between stations 3 & 4 (15.8 - 18.0 km)*
4 Stretch between stations 4 & 5 (18.0 - 19.9 km)*
5 Stretch between stations 5 & 6 (19.9 - 23.2 km)*
6 Stretch between stations 6 & 7 (23.2 - 27.8 km)*
7 Initial value for period free of ice.

*from designated point of origin

"From comparisons, we see that the periods of greatest channel narrowing on the three lower stretches occured when the ice edge pulsated. It was noticeable, that the greatest degree of constriction held out for only brief intervals in each zone. This was associated with the appearnace of openings in the frazil layer, which appeared on the surface, but more frequently, were hidden beneath the ice.

"The break up of the ice jam was promoted, to a certain degree, by icebreakers.

"The channel constriction, in the order of 0.5-0.7 remained relatively stable for a few days in a number of stretches. The regions of greatest constriction wer subdivided on the basis of hydraulic characteristics ($\frac{F_x}{F_{nc}}$). These permitted investigations of jam developments from period to period in a greater or lesser degree, and capacitated the establishment of the most hazardous zone of the ice jam, which, in turn, had great significance for installation of preventive measures.

"We can compute, then, the total load of the frazil layer and ice in the jam, and its extent. The thickness was calculated by means of equation (18), where H_0 was taken from diagram 4; ΔH, from Table 7; and the size of the hydraulic radius R_x, calculated by equation (14).

"The values of the water-transmissivity (K_x), with calculation of R_x, are given in Table 6; the width of the river (B) from diagram 4; and the reduced roughness coefficient is accepted as 0.030.

"The indicated value of the reduced roughness coefficient was derived by two methods: from adaptations of data over several years of observations of water levels in a series of stations, with calculations of water discharge in the jam-free freezeup (equation 7), and on the basis of calculations of $\frac{n_m}{n_0}$ after data of measured current velocities.

"The total thickness of frazil and ice in the jam (h_m) is calculated by equation 19. The extent of the jam is found by multiplication of h_m in the area of a given stretch.

"The combined results of the calculation are illustrated graphically in diagram 7; the diagram was constructed on the basis of data from a 16 hour term on 31/XII.

"The horizontal line on the diagram represents the conditional horizon which marks the river depths, based on hydrographic data (diagram 4). The average depth for each individual stretch is indicated by the dotted line. The area above the horizontal line indicates the level rise for observed term (according to Table 7). From the value of K (Table 6), the hydraulic radius is calculated in each reach of observation. The value $2R_x$ is indicated, on diagram 7, just above the bottom line.

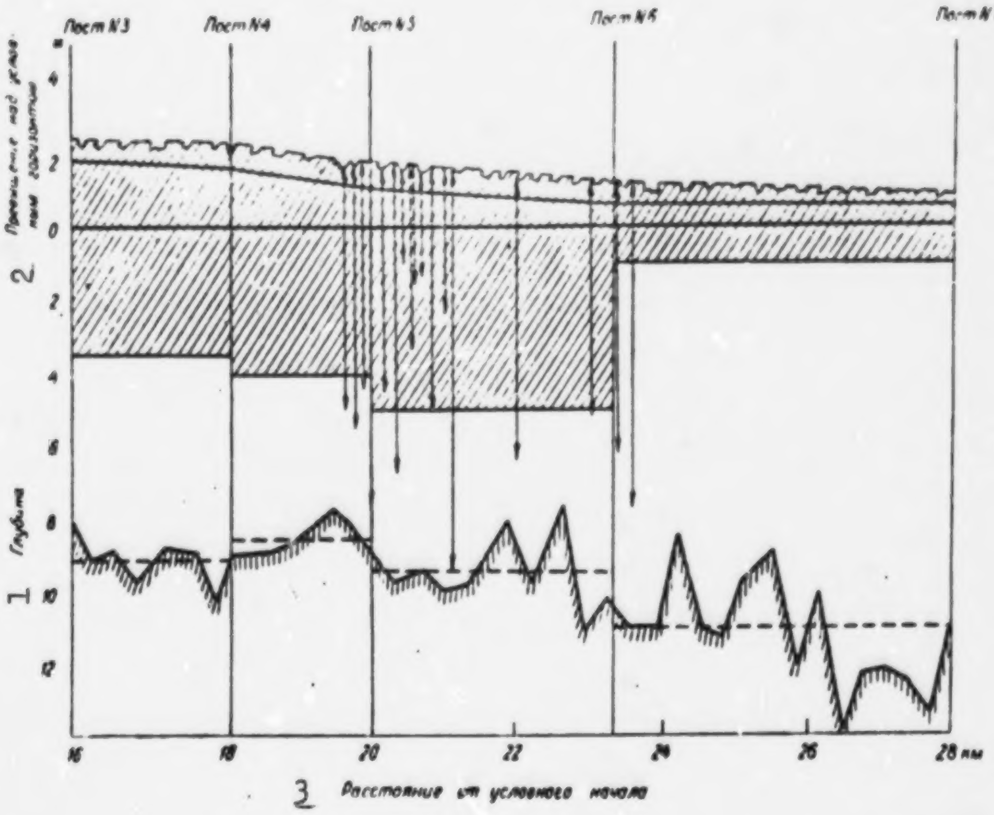
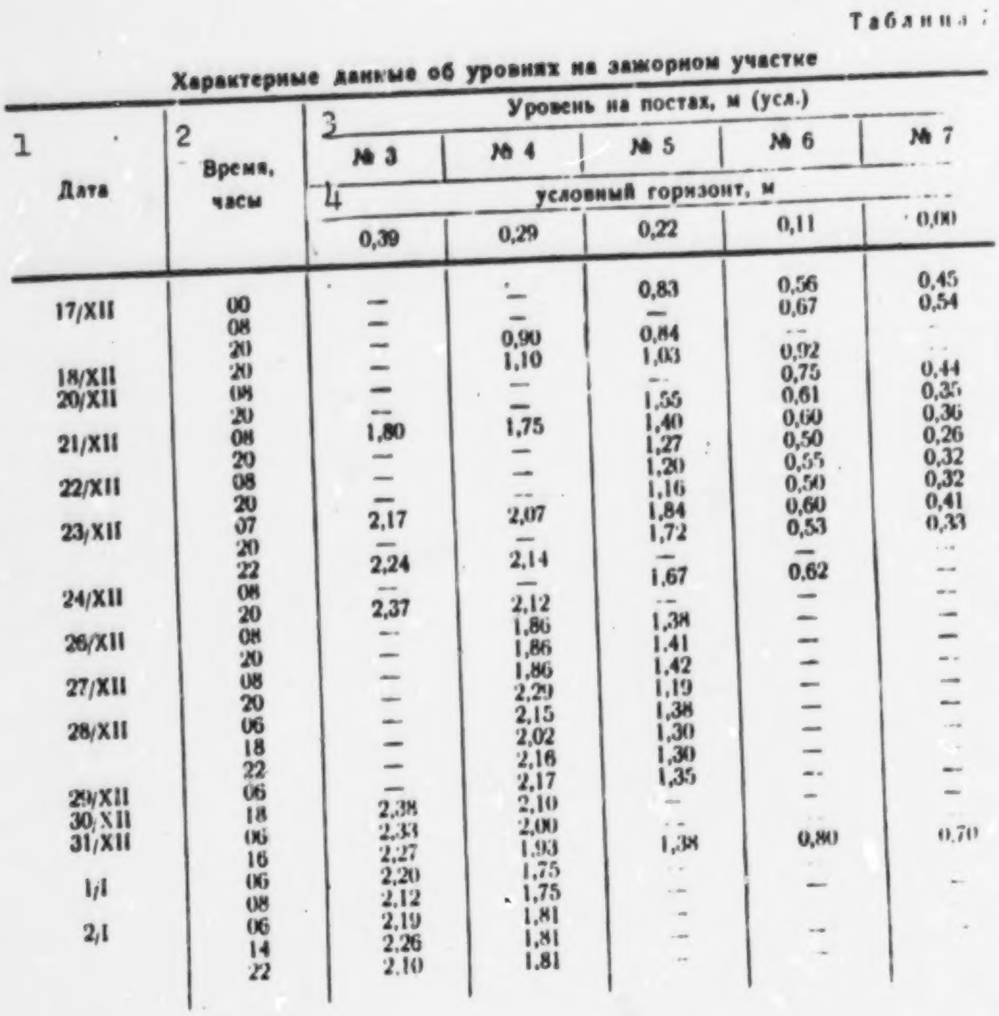


DIAGRAM 7 Thickness of frazil layer and ice in the jam (shaded area) existing on December 31, calculated by equations (18) & (19). (Berdennikov, 1956)

1 Depth
2 Excess over the designated horizon
3 Distance from point of origin
4 Arrows indicate thickness of frazil and ice layer on December 31.



Таблица

Характерные данные об уровнях на заторном участке

1 Дата	2 Время, часы	3 Уровень на постах, м (усл.) № 3	№ 4	№ 5	№ 6	№ 7
		4 условный горизонт, м 0,39	0,29	0,22	0,11	0,00
17/XII	00	—	—	0,83	0,56	0,45
	08	—	—	—	0,67	0,54
	20	—	0,90	0,84	—	—
18/XII	20	—	1,10	1,03	0,92	—
20/XII	08	—	—	—	0,75	0,44
	20	—	—	1,55	0,61	0,35
21/XII	08	1,80	1,75	1,40	0,60	0,36
	20	—	—	1,27	0,50	0,26
22/XII	08	—	—	1,20	0,55	0,32
	20	—	—	1,16	0,50	0,32
23/XII	07	2,17	2,07	1,84	0,60	0,41
	20	—	—	1,72	0,53	0,33
	22	2,24	2,14	—	—	—
24/XII	08	—	—	1,67	0,62	—
	20	2,37	2,12	—	—	—
26/XII	08	—	1,86	1,38	—	—
	20	—	1,86	1,41	—	—
27/XII	08	—	1,86	1,42	—	—
	20	—	2,29	1,19	—	—
28/XII	06	—	2,15	1,38	—	—
	18	—	2,02	1,30	—	—
	22	—	2,16	1,30	—	—
29/XII	06	—	2,17	1,35	—	—
30/XII	18	2,38	2,10	—	—	—
31/XII	06	2,33	2,00	—	—	—
	16	2,27	1,93	1,38	0,80	0,70
1/I	06	2,20	1,75	—	—	—
	08	2,12	1,75	—		
2/I	06	2,19	1,81	—	—	—
	14	2,26	1,81	—	—	
	22	2,10	1,81	—		

TABLE 7 Characteristic data on the levels of the jammed stretch. (Berdennikov, 1956)

1 Date
2 Time, in hours
3 Levels at stations, in meters
4 Conditional horizon, in meters.

"Data on the maximum development of jams in the observed stretches, the greatest degree of immersion, the thickness of the frazil layer and ice, and the limits of frazil accumulation, are given in Table 8. Also included there are the general hydrographic factors necessary for calculations.

"In comparing the calculated thicknesses of the frazil and ice (diagram 7 and Table 8), with the observed data, obtained from ice-measuring surveys (Table 9), it must be kept in mind that the observed data does not represent the entire reach of the river, that is, its continuous route, but refers only to the separate observed sections; and the cross-section refers only to the lower portion of the 16 km. stretch (diagram 5). Another reason why the cross-sectional measurements cannot be compared with the calculations is that they were taken on 8/II, that is, almost 1.5 months after the ice jam formed, and by this time, the frazil in the jam had disintegrated considerably.

"Since the frazil cannot be displaced from the lower stretches of the river to the higher ones, the total amount of ice materials used up in the formation of the jam, on the entire 16-km course, is obtained simply from the sum of the maximum amounts of materials in the stretches; that is, from each individual stretch (Table 8), observed within a specific period, beginning with the earliest period in the lowest stretch and ending with the final period in the highest stretch.

"For the four stretches indicated in Table 8, the obtained sum of the frazil volume was $30.6 \cdot 10^6 m^3$ or $17.8 \cdot 10^6 t$.

"By a similar means, we calculated the amount of frazil in the stretch between stations 1 and 3 and obtained the following data: the frazil thickness = 5.3m; the volume was $8.6 \cdot 10^6 m^3$ for a stretch 4.3 km long.

"The total amount of ice on the observed stretch, 16.3 km long, was computed as $39.2 \cdot 10^6 m^3$ or $22.8 \cdot 10^6 t$. This quantity can be compared with data in Table 3, where the daily amounts of frazil, which approached the ice edge, are given.

"According to data in diagram 6, the ice edge shifted within the limits of the observed ice jam stretch, in the period from 17/XII to 2/I inclusive. Taking from Table 3, the value of N_o for the indicated term (17 days), we obtain the total amount of ice, participating in the frazil drift, to be around $24 \cdot 10^6 t$ of ice; this is found to be in good agreement with the amount obtained by calculations, that is, $22.8 \cdot 10^6 t$."

Berdennikov (1958) applies the principle of the above investigation to the Angara & Yenisey Rivers.

In another report by Berdennikov (1957) the two previous investigations are described. In addition he includes a section on the "state and movement of frazil accumulations". The mechanism of sludge accumulation is investigated from a thermodynamic point of view in the light of the kinetic theory of solids. The analysis is made using a snow compaction analogy.

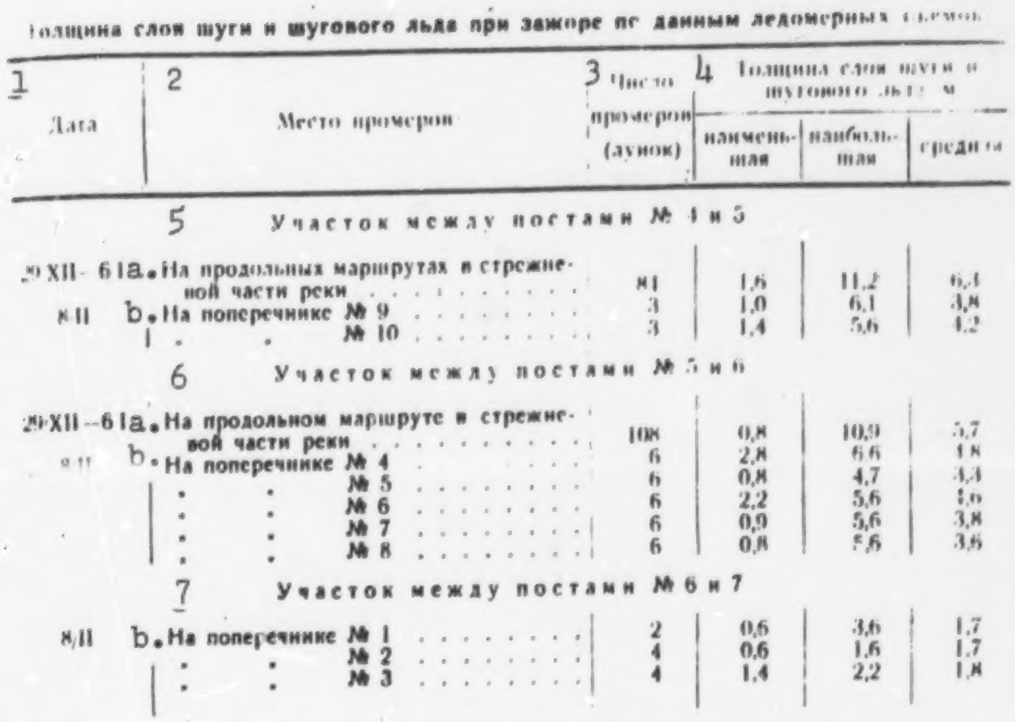
Таблица 8

Общие гидрографические данные для участков и наибольшие за период зажора величины общей толщины и погруженной части слоя шуги и льда, а также объема шуги на участке

	1 Участок между пунктами № 3 и 4	2 Участок между пунктами № 4 и 5	3 Участок между пунктами № 5 и 6	4 Участок между пунктами № 6 и 7
5 **Общие сведения**				
a. Длина L, м	2200	1900	3300	4600
b. Ширина B, м	319	357	467	380
c. Площадь зеркала, м²	$0,70 \cdot 10^6$	$0,68 \cdot 10^6$	$1,54 \cdot 10^6$	$1,75 \cdot 10^6$
d. Глубина при условном горизонте H_0, м	9,14	8,53	9,45	11,00
e. Уклон начальный i_0	0,000045	0,000037	0,000033	0,000024
6 **Сведения о наибольшем развитии зажора**				
a. Срок	2.I 14 час.	27/XII 20 час.	23 XII 7 час.	20 XII 20 час.
b. Глубина при зажоре $H_0 + \Delta H_x$, м	10,82	10,02	10,51	11,54
c. Гидравлический радиус R_x, м	2,67	1,80	1,75	3,31
d. Погружение льда и шуги $h_{погр}$, м	5,5	6,4	7,0	4,9
e. Толщина слоя льда и шуги $h_ш$, м	6,0	7,0	7,6	5,4
f. Объем зажора $h_ш LB$, м³	$4,2 \cdot 10^6$	$4,8 \cdot 10^6$	$11,8 \cdot 10^6$	$9,8 \cdot 10^6$
7 Всего	$30,6 \cdot 10^6$ м³ или $17,8 \cdot 10^6$ т			

TABLE 8 General hydrographic data for the stretches and the highest values of thickness and submergence of frazil and ice during the jam; also, volume of the frazil. (Berdennikov, 1956)

1 Stretch between # 3 & 4
2 Stretch between # 4 & 5
3 Stretch between # 5 & 6
4 Stretch between # 6 & 7
5 General information
  a) Length "L", meters
  b) Width "B", meters
  c) Area of river's mirror, meters^2
  d) Depth at designated horizon, H_o, meters
  e) Initial slope i_o
6 Information on highest jam development
  a) Terms
  b) Depth during jam, $H_0 + \Delta H,$, meters
  c) Hydraulic radius R_x, meters
  d) Submergence of frazil & ice $h_{погр}$, meters
  e) Thickness of frazil & ice layer $h_ш$, meters
  f) Volume of jam $h_ш LB$, meters^3.
7 Total



Толщина слоя шуги и шугового льда при зажоре по данным ледомерных съемок

1 Дата	2 Место промеров	3 Число промеров (лунок)	4 Толщина слоя шуги и шугового льда, м		
			наименьшая	наибольшая	средняя
	5 Участок между постами № 4 и 5				
29 XII—6 I	a. На продольных маршрутах в стрежневой части реки	81	1,6	11,2	6,4
8 II	b. На поперечнике № 9	3	1,0	6,1	3,8
	„ „ № 10	3	1,4	5,6	4,2
	6 Участок между постами № 5 и 6				
29 XII—6 I	a. На продольном маршруте в стрежневой части реки	108	0,8	10,9	5,7
8 II	b. На поперечнике № 4	6	2,8	6,6	4,8
	„ „ № 5	6	0,8	4,7	3,3
	„ „ № 6	6	2,2	5,6	4,6
	„ „ № 7	6	0,9	5,6	3,8
	„ „ № 8	6	0,8	5,6	3,6
	7 Участок между постами № 6 и 7				
8 II	b. На поперечнике № 1	2	0,6	3,6	1,7
	„ „ № 2	4	0,6	1,6	1,7
	„ „ № 3	4	1,4	2,2	1,8

TABLE 9 Thickness of frazil layer and frazil ice during the jam, according to ice-measuring surveys. (Berdennikov, 1956)

1 Date
2 Location of measurements
3 Number of measurements
4 Thickness of frazil layer and frazil ice, in meters: smallest, largest, average
5 Stretch between stations 4 & 5
  a) on the longitudinal routes
  b) on transverses
6 Stretch between stations 5 & 6
7 Stretch between stations 6 & 7

"The examined mechanism of cohesion in intra-water ice, as expressed by the formation of the more or less solid connecting strips of ice between the particles, served as a basis for analysis of dynamic conditions during the initial stage of the ice jam. After cessation of free transit, the state of the frazil masses can be described... considering the activity of tangential stresses of the stream and the resistance of the frazil layer. The equilibrium is expressed by the equation:

$$h(\tau_0 + \eta\frac{dv}{dy} = \frac{1}{2}\gamma iHx.$$

where h - is the thickness of the frazil layer
τ_0 - is the initial splitting direction
η - is the viscosity coefficient
H - is the depth of the stream under the frazil layer

"In the first stage of jam development, the thickness of the frazil layer, all things being equal, must increase proportionally to the slope. This correlation... is observed in reality."

"The equation stated above describes most fully the third stage of the jams, that is, the mobility of the frazil masses, since these phenomena are due entirely to dynamic causes.

"A distinct problem is presented by the study of physical characteristics (η and τ) of the frazil layers. Literature suggests that the viscosity coefficient η is related to air-temperatures (Yestifeyev, 1951 and Berg, 1956). However, such fragmentary information is insufficient for analysis and calculation of dynamic conditions during the initial stages of ice jam formation and movement. Even less is known about the initial splitting directions since this characteristic was determined by us only in the order of (0.01 - 0.02 kg/cm^2) and was not studied in reference to the period of frazil existence, air-temperatures, and therms of the water. Both of the named characteristics require further investigation, both in field and laboratory conditions."

Several papers on the mechanism of ice jam formation and growth have been published by members of the LaSalle Hydraulic Laboratory (Montreal, Canada). In one of the most recent, the mechanism of ice jam formation is analyzed for straight rivers of uniform slope, roughness, cross section, and flow (Pariset, Hausser and Gagnon, 1966). They advise, however, that model studies usually provide the only practical solution.

"As winter begins, large quantities of ice floes form on rivers flowing in cold regions. The floes are carried downstream by the current until they reach an artificial obstacle such as a bridge pier in a low velocity zone, or a river section where slower surface currents and topography cause the floes to wedge, and result in the eventual build-up of a continuous ice bridge. As new ice floes arrive and come to rest on the ice bridge, the front of the cover proceeds upstream at a rate depending on the quantity of ice coming from upstream.... In some sections where the velocity is slower, a relatively thin ice cover progresses quickly and smoothly, whereas in other sections considerable local thickening-termed ice jamming-always occurs before the progression of the cover can proceed upstream. In the Montreal area of the St. Lawrence River, thickening of the ice cover to 30 ft. has been measured (Cousineau, 1964). Even more damaging ice jams can form during the late winter when the warmer rays of the sun and the first increase of flow combine to dislocate the ice cover. A large volume of ice is thus released and can jam downstream under an ice cover which is not yet weakened. This is typical in some rivers flowing north to colder regions.

"In small and shallow rivers, dislocation of ice covers may result in a concentration of ice floes sufficiently large to overcome the carrying capacity of the flow, in some sections. Temporary pile-ups may occur, diminishing or even nullifying the discharge downstream until the jam breaks up....

"Analysis of the Phenomena. -- To simplify the analysis, an ideal rectangular channel of constant shape and roughness was considered.

"The forces acting on the ice cover over the width and a differential length, dL are (Fig. 1) as follows:

1. The hydrodynamic force of the current against the upstream limit of the cover, f_1 per unit width;

2. the shearing stresses of flowing water under the cover, f_2 per unit area;

3. the component of the weight of the cover in the direction of the slope of the ice-water interface f_3 per unit area;

4. the shearing stress of the wind on the cover which, in most practical cases, can be neglected with thick ice cover and;

5. the reaction of the banks consisting of a cohesive contribution and an ice-over-ice friction term ($\tau l + tg\,\phi f_t$) dL, in force per unit length, in which f_t = the transversal stress pushing the cover against the bank, = $K_1 f$, in which f = longitudinal stress and K_1 = a coefficient equal or smaller than 1 depending on the active or neutral state of the granular mass of ice.

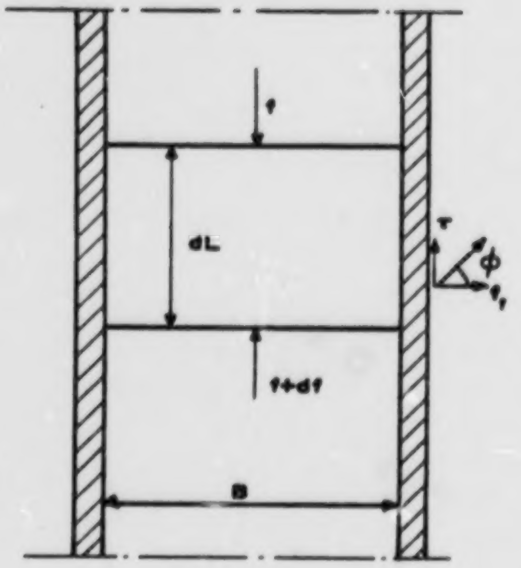

f
dL
τ
φ
f₁
f+df
B

FIG. 1.—DEFINITION SKETCH
(Pariset, Hausser, Gagnon, 1966)

"The equilibrium of a differential length, dL, of the cover results in

$$df\,B + 2\,(\tau\,t + t\,g\,\phi\,K_1\,f)\,dL = (f_2 + f_3)\,B\,dL \tag{1}$$

for dF, the resultant differential force per unit width of a given section of cover, in which B=width of channel; t=cover thickness; τ =the cohesion of the ice on the banks, in force per unit area; $t\,g\,\phi$ =the friction coefficient of the ice; and L=the distance between the upstream edge of the cover and the section under study.

"Integrated, Eq. 1 gives

$$f = \frac{B}{2\,K_1\,t\,g\,\phi}\,(f_2 + f_3) - \frac{\tau\,t}{K_1\,t\,g\,\phi} - [\alpha]\,\exp - \frac{2\,K_1\,t\,g\,\phi\,L}{B} \tag{2}$$

in which

$$\alpha = \left[\frac{B}{2\,K_1\,t\,g\,\phi}\,(f_2 + f_3) - \frac{\tau\,t}{K_1\,t\,g\,\phi} - f_1\right] \tag{3}$$

and f_1=the boundary condition, i.e., the thrust on the cover at L=0.

"Eq. 2 shows how the external resultant force, f, on the cover varies with L, the distance between the upstream edge of the cover and the section under consideration.

"Also, Eq. 2 allows calculation of the ice-cover thrust on a dam or boom. However, Eq. 2 does not consider thermal stresses on a consolidated cover. The value of f given by Eq. 2 must be multiplied by $t\,g^2\,(\pi/4 \pm \phi/2)$ depending on whether the boom mobilizes the active or neutral state of the ice cover. Two cases are now considered.

"First Case.--Narrow Rivers. -- If α in Eq. 3 is negative, Eq. 2 then shows that the resultant stress, f, will be a maximum for L=0 and

$$f = f_1 \tag{4}$$

"Therefore, the thrust on the cover is a maximum at its upstream edge. As the cover progresses upstream, the extent of thrust that is absorbed by the banks in a given section grows faster than the additional hydrodynamic forces exerted on the cover.

"From the standpoint of ice-cover formation, the river is said to be 'narrow.' The thickness of the ice cover is governed by conditions at its upstream edge and will not be altered during its progression.

"The equilibrium conditions can be obtained from Fig. 2.

"If the head loss between section 1 and 2 immediately upstream and downstream at the front of the cover is neglected,

$$H + \frac{V^2}{2g} = h + \frac{V_u^2}{2g} + t_2 \qquad (5)$$

in which H = depth of water, V = mean velocity, and V_u = velocity underneath the ice cover.

"In addition, if ϵ = the void ratio in the cover, the equilibrium of the ice at the water level requires that

$$t_2\ (\rho - \rho')(1 - \epsilon) = t_1\ \rho'\ (1 - \epsilon) \text{ or } t_1 = t_2\ \frac{\rho - \rho'}{\rho'} \text{ and } t_2 = t\ \frac{\rho'}{\rho} \qquad (6)$$

If the void ratio is the same in the part of the cover below the water level and the part above the water level, it plays no role in the equilibrium conditions.

"To prevent water from spilling onto the front of the cover,

$$H + \frac{V^2}{2g} \leq h + t \qquad (7)$$

Combining Eqs. 6 and 7" and from "tests conducted in the laboratory flume... the cover progresses with a thickness given by

$$V_u = \sqrt{2g\,\frac{\rho - \rho'}{\rho}\,t} \qquad (9)$$

"As the velocity, V_u, is not available directly, it can be replaced by the velocity in the front of the cover; hence

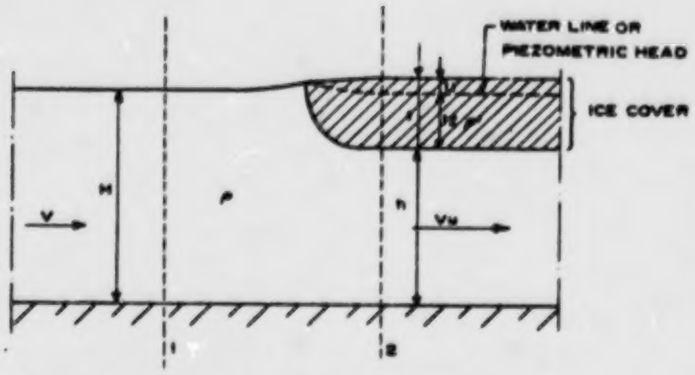

WATER LINE OR
PIEZOMETRIC HEAD
ICE COVER
H
V
ρ
h
Vu
1
2

FIG. 2.—ANALYSIS OF EQUILIBRIUM CONDITIONS AT UP-STREAM EDGE OF COVER (Pariset, Hausser, Gagnon, 1966)

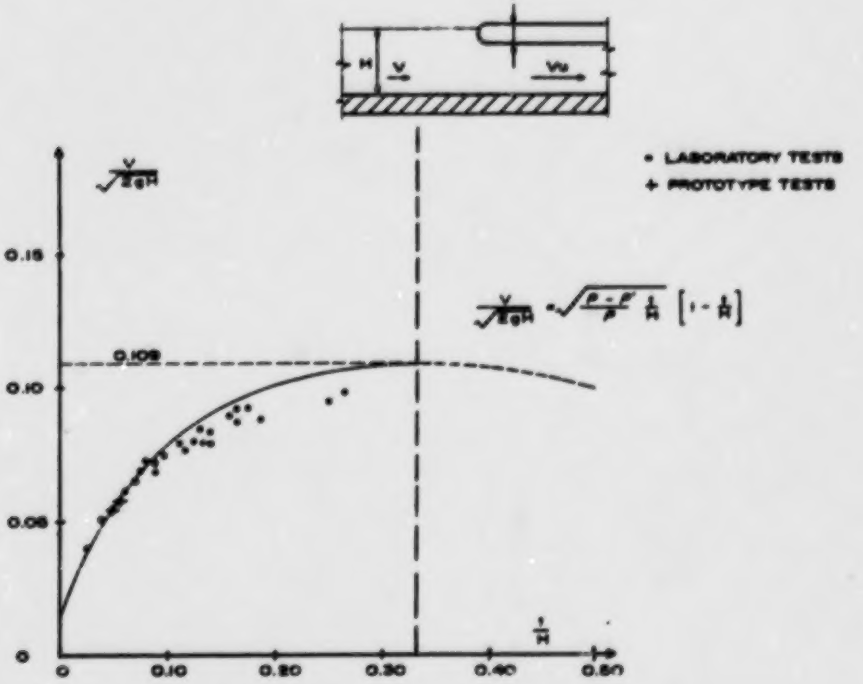


FIG. 3.—THICKNESS AT UPSTREAM EDGE OF COVER
(Pariset, Hausser, Gagnon, 1966)

$$V = V_u \left(1 + \frac{V^2}{2\,g\,h} - \frac{t}{H}\right) \qquad (10)$$

Because $V^2/2\ g\ H$ is usually negligible, Eq. 10 becomes

$$V = \sqrt{2\,g\,\frac{\rho - \rho'}{\rho}\,t}\,\left(1 - \frac{t}{H}\right) \qquad (11)$$

"Eq. 10 gives the thickness at the edge as a function of a modified Froude number and is plotted on Fig. 3.... As can be seen, the experimental measurements verify the theoretical curve. The few experimental data obtained with real ice on outdoor canals or rivers leads to the supposition, at least as a first approximation, that the density of the cover is equal to 0.92, which would indicate that the void ratio is either nil or, more likely, is the same for the parts of the cover both above and below the water level.

"Fig. 3 shows that the thickening at the upstream edge does increase with increasing flow velocity or decreasing depth, but that a maximum exists at $t/H = 1/3$ beyond which the added thrust from the shallower water passage is no longer compensated for by the added buoyance resulting from the thickening of the cover. Therefore, this condition is unstable; all ice floes sink beneath the cover and pile up. This is the first type of ice jam in a so called 'narrow channel.' The phenomenon continues until the head loss created by the piling-up raises the upstream water levels so that the velocities become sufficiently low to allow a new progression of the cover. The fact that $V^2/2\ g\ H$ is no longer negligible under these conditions explains the increasing divergence between the experimental and theoretical results in this part of the curve....

"Second Case. -- If α in Eq. 3 is positive, then the thrust in a section increases with its distance from the front edge of the cover and approaches the limit

$$\lim f = \frac{B}{2\,K_1\ t\ g\,\phi}\ (f_2 + f_3) - \frac{\tau\ t}{K_1 t\ g\,\phi} \qquad (12)$$

"The cover will thicken through successive shoves until its internal resistance, f_5, in a given section is equal to the sum of the external forces.

"The internal resistance, f_5, will vary from

$$\rho' \left(1 - \frac{\rho'}{\rho}\right) \frac{g\,t^2}{2}$$

if it is supposed that the agitation of water fluidizes the cover, to the more probable value of

$$\rho' \left(1 - \frac{\rho'}{\rho}\right) \frac{g\,t^2}{2}\; tg^2 \left(\frac{\pi}{4} + \frac{\phi}{2}\right)$$

if it is assumed that a complete mobilization of the passive resistance of the cover is established. Therefore,

$$f_5 = \rho' \left(1 - \frac{\rho'}{\rho}\right) \frac{g\,t^2}{2}\; K_2 = \frac{B}{2\,K_1\,tg\,\phi}\,(f_2 + f_3) - \frac{\tau\;t}{K_1\;tg\,\phi}$$

"Note that K_1 and K_2 are functions of ϕ . Including all parameters depending on ϕ as the constant

$$\mu = K_1\,K_2\,tg\,\phi \tag{14}$$

it is possible to derive

$$\rho' \left(1 - \frac{\rho'}{\rho}\right) \frac{g\,t^2}{2} = \frac{B}{2\,\mu}\,(f_2 + f_3) - \frac{\tau\;t}{\mu} \tag{15}$$

"The usual assumptions of hydraulics allow

$$f_3 = \rho\,g\,\frac{V_m^2}{C^2} \tag{16}$$

and

$$f_2 = \rho' g t \frac{V_u^2}{C^2 R_H} \qquad (17)$$

in which R_H = the hydraulic radius of the water passage. Eqs. 16 and 17 are valid if the Chezy coefficient, C, has the same value under the ice cover that it has for the river bed, which is approximately the case for the sections of the St. Lawrence River and Beauharnois Canal studied. If not, then a slightly more complicated formula will have to be used instead of Eqs. 16 and 17.

"The thickness of the cover in wide rivers is given by

$$\frac{B V_u^2}{\mu C^2 H^2}\left(1 + \frac{\rho' t}{\rho R_H}\right) = \frac{2 \tau t}{g \rho \mu H^2} + \frac{\rho'}{\rho}\left(1 - \frac{\rho'}{\rho}\right)\frac{t^2}{H^2} \qquad (18)$$

"Fig. 4 shows the application of Eq. 18 to a rectilinear channel having a 4,000-ft. width, a 30-ft. depth, and a Chezy coefficient of 60.

"Curve B gives the thickness of the upstream edge of the cover (Eq. 11) as a function of the flow velocity. Curve A gives the final thickness of the cover to support the ice thrust after progression of the cover (Eq. 18). Curve A' applies for the same conditions but when the influence of the ice cohesion is negligible. The curves indicate that considerable supplementary thickening occurs as a result of the increase of resultant forces, as soon as the flow velocity surpasses 2 fps.

"Point C corresponds to the transition from a 'narrow' to a 'wide' river, clearly showing how a particular river can be 'narrow' for low velocities, and 'wide' for faster velocities. It can be seen further that curves A and A' go through a maximum corresponding to a thickness that cannot be exceeded without compromising the equilibrium of the cover. This denotes a second type of ice jam which, as noted above, stops cover progression until the rise in upstream water level results in a sufficient decrease in velocity to allow a new progression of the cover.

"A comparison of curves A and A' giving cover thickness with or without cohesion shows that although cohesion is important for thin covers, it has practically no effect for thick ice jams.

"Two types of ice jams are defined but observations show that transportation of ice under the cover may also influence cover formation and thickness, as explained later herein.

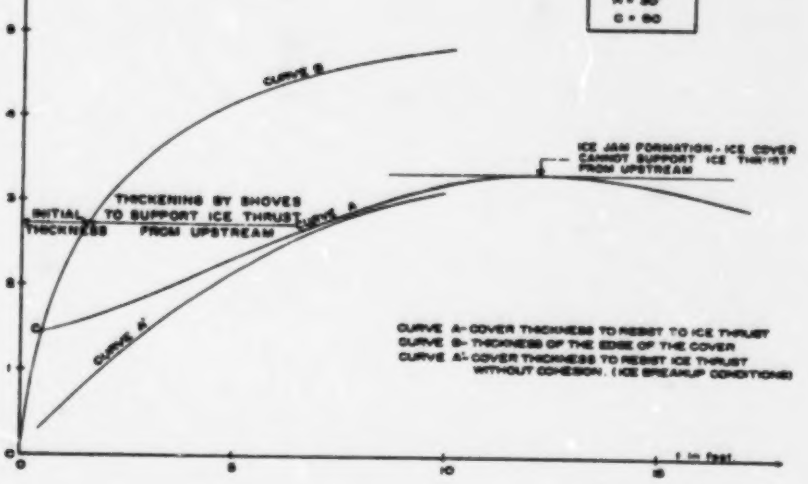


FIG. 4.—THICKENING OF COVER FOLLOWING ICE THRUST
(Pariset, Hausser, Gagnon, 1966)

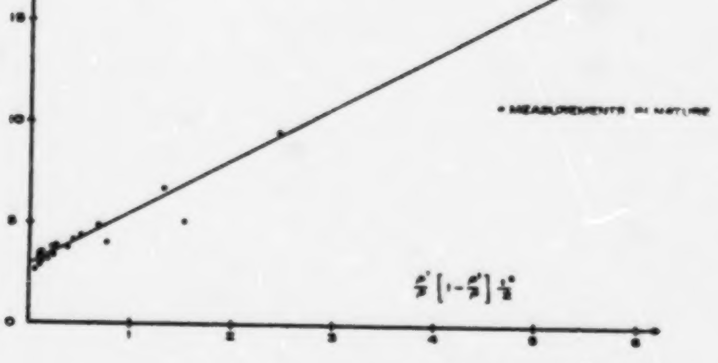


FIG. 5.—DETERMINATION OF CONSTANTS τ AND μ
(Pariset, Hausser, Gagnon, 1966)

"Evaluation of Constants. -- It has been shown that the jamming phenomenon can be described mathematically, but that the knowledge of certain constants is necessary to obtain numerical results.

"These constants are ρ', the specific mass of ice, C, the Chezy coefficient under an ice cover, μ, a coefficient characterizing the friction of ice, and τ, the cohesive strength of the ice at the banks....

"The investigation of the St. Lawrence River in the Montreal and Beauharnois Canal area has resulted in the determination of the following values for K (of the Chezy coefficient): At the formation stage of cover $25 < K < 30$, and at the later stages of a stable cover $35 < K < 45$....

"Coefficients μ and τ can be determined through prototype measurements; a typical example is given in Fig. 5 based on analysis of measurements taken on the Beauharnois Canal....

"It was found, in many instances, that μ had a value of 1.28, whereas the product τt varied from 75 lb per ft to 91 lb per ft (Pariset and Hausser, 1961).

"Note that in many cases, and particularly at break-up, the cohesive action is destroyed," - so that this term in Eq. 18 equals zero.

"Analysis of Results. -- It is possible to consider Eq. 18; however, a simpler presentation can be given assuming the cohesive term to be negligible, which is sometimes possible (thick ice jams), or which in every case will give a safety factor corresponding to the maximum thickening. The general expression for wide covers can be written as

$$X = \frac{Q^2}{B\,C^2\,H^4} = \frac{B\,V^2}{C^2\,H^3} = \frac{\mu\left(1 - \frac{\rho'}{\rho}\right)\frac{\rho'}{\rho}\left(\frac{t}{H}\right)^2\left(1 - \frac{\rho'\,t}{\rho\,H}\right)^3}{1 + \frac{\rho'}{\rho}\,\frac{t}{H}} \qquad (20)$$

... For... $\rho' = 0.92$ and $\mu = 1.28$, Eq. 20 gives... Fig. 6. Characteristic points inside the bell-shaped curve indicate stable covers; points outside indicate constant deformation of the cover....

"Maximum Discharge Allowing Formation of Ice Cover. -- Regardless of its relative thickness, a stable cover can exist only if

$$\frac{B\,V^2}{C^2 H^3} = \frac{Q^2}{B\,C^2\,H^4} < 2.8 \times 10^{-3} \qquad (21)$$

which corresponds to

$$Q \leqslant 0.053\, H^2\, C\sqrt{B} \qquad (22)$$

"If Eqs. 21 and 22 are not verified, thickening and shoving will continue until a stable point is reached through the increase in depth, H, following the head losses that result from piling-up of ice downstream.

"Eq. 22 shows the advantage of having a deep and narrow channel, or even, in some cases, of dividing an existing canal by a longitudinal dike.

"Evolution of Ice Cover with Constant Discharge. -- The thickness of the frontal edge of the cover is given by Eq. 11 and, as shown, is always smaller than one-third the depth. The corresponding point on Fig. 6 therefore must be to the left of the vertical line t/H=0.33. This point, as in B', can be inside the stability curve or, as in A, can be outside it.

"In the first case, the river is 'narrow'; the thickness of the cover is sufficient to withstand forces acting during its progression. However, the thickness can be modified by the transportation of ice under the cover.

"In the second case, the river is'wide'; the thickness of the cover is not sufficient to withstand the increasing forces acting on it during its progression. The cover thickens, and point A moves to the right until it reaches position A' on the stability curve.

"Evolution of Ice Cover Resulting from Ice Deposits. -- The flow velocity at the upstream edge of the ice cover can be sufficient for the carrying of ice floes under the cover. These floes can either be transported a long distance downstream or deposited under the same manner as sands and gravel are depositied on river beds.

"It was verified that, at least in the first approximation, the experimental law of Meyer-Peter describing bed load transportation can be applied.

"This phenomenon can thicken an ice cover, for instance, downstream of a section of rapids where no ice cover exists. An initially stable cover, such as B' can, in this manner, reach the upper limit of stability B" and even thicken beyond this limit to B'". Hence, it again will be subjected to movement until a new equilibrium is reached through an increase of H....

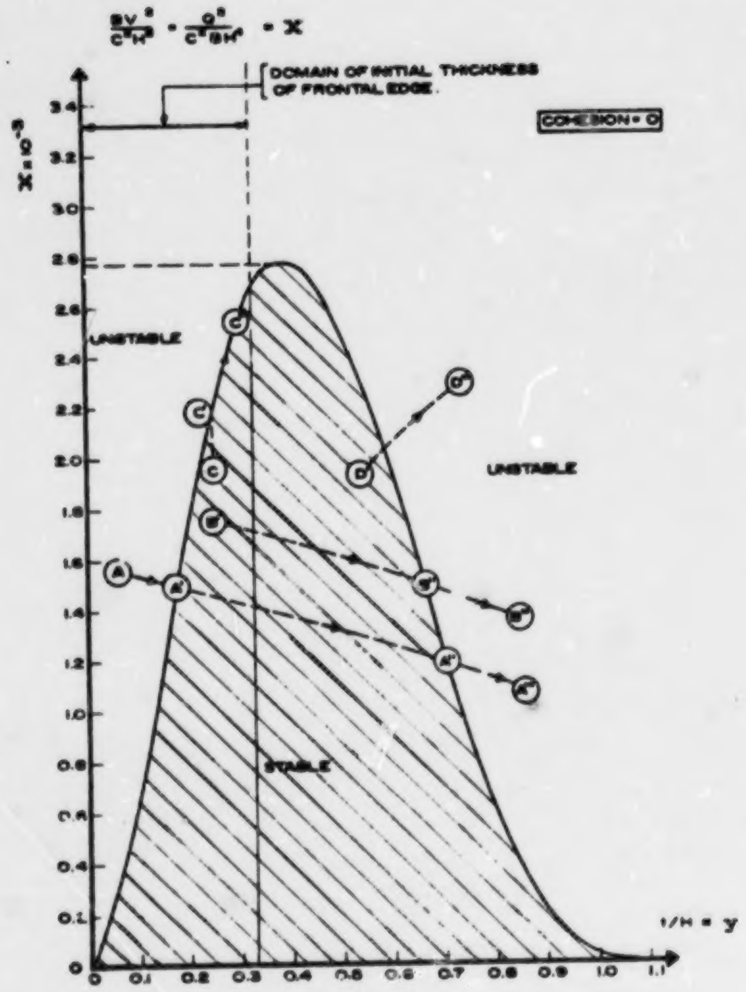


FIG. 6.—DIMENSIONLESS STABILITY DIAGRAM
(Pariset, Hausser, Gagnon, 1966)

"It must be noted that, in some cases, the upstream edge of the cover cannot progress and reach its normal thickness as long as the flow under the cover carries away all incoming drifting ice.

"Another cause of evolution of an ice cover is the deposition of frazil ice under it....Thickening of the cover can, in this case, be calculated by settling basin equations....

"Evolution of Ice Cover with Variable Discharges. -- Two cases can be considered:

1. Channels where depth, H, does not vary with discharge. --This is a typical case of rivers or power canals upstream of a dam. It can be seen on Fig. 6 that starting from an initially stable cover, C, the discharge can be increased to a point corresponding to C' without any instability.... At C', the limit of stability is reached and any further increase of discharge will force the cover to thicken, C' to C".

"If the discharge exceeds the critical value mentioned previously, it will no longer be possible to attain a stable equilibrium; the cover will recede and jam until the discharge is reduced or the depth, H, is increased to sufficiently raise the critical value of the discharge.

2. Natural channels. -- In natural channels the discharge law is of the type

$$Q = K' B H^n \tag{23}$$

in which K' and n = constants, and n is usually lower than 2. Therefore

$$Q^2/C^2 B H^4 \text{ becomes } \frac{Q^{(2-4/n)} (K' B)^{4/n}}{B C^2}$$

and t/H becomes

$$\frac{t (K' B)^{1/n}}{Q^{1/n}}$$

"If the discharge is reduced, both t/H and Q^2/C^2 BH^4 will increase. Point D corresponding to initial conditions will move to D' and D".

"Therefore, a reduction in discharge can produce an instability and induce a jam. It should be noted that such an instability is more likely to occur if the original location of the characteristic point is selected near the descending part of the curve. This is likely to happen during the ice break-up, as a result of the large ice discharge carried by the river, resulting in rapid thickening of the covers. This source of instability does not imply necessarily that in the presence of ice, higher stages will be reached at lower discharge, but that a greater proportion of the elevation of the stage can be attributed to thickening compared to the normal stage governing parameters.

"Remarks. -- It is important to note that most of the equations and graphs presented thus far have been established for straight rivers or channels of uniform slope, roughness, cross section, and flow, for the sake of simplification and ease of analysis.

"...Thus, if the basic analysis is still valid, Eqs. 11 and 18 can no longer be applied and a particular analysis based on the exact topography must be performed for each case, taking into account variations of roughness, width, depth, influence of convergences or divergences on the fraction of forces transmitted to the shores, etc."

Field verification, application of the theory, and scale model tests are described in the remainder of the report.

Methods similar to those described in the above paper are used by Hausser (1964) to analyze the effects of channel modifications on ice jamming near Montreal.

In another recent article, Pariset and Gagnon (1967) further examine the mechanism of jam formation. The following is a summary of a translation of their paper.

"Description of the phenomena

"Immobilized on any obstacle, or simply buttressed, on the same in a narrow reach, the cover can progress upstream in a relatively shallow thickening.

"If this progress leads the ice cover into a zone where the velocities are very high, the cover cannot progress upstream, all the ice blocks drifting with the current are plunged beneath the ice cover. They are channeled under the cover until they reach zones of lower energy downstream where they are deposited under the previously formed ice cover, as indicated in figure 1. They create in this manner an ice dam in which the thickness grows larger gradually as the contribution of ice continues. The energy under the ice cover increases until it attains a strength such that the ice blocks cannot be stopped, or in case they are trapped, they will be almost immediately placed back in motion; in this case, the energy of flow is said to be 'the velocity beginning of dragging' (vitesse de debut d'entrainement).

"For a loss at each stage in the evolution of the ice dam, there corresponds a certain release between the lower part of the cover and the bed of the stream. If the loss by filling the width of the stream course is sufficiently low that this release becomes of the order of

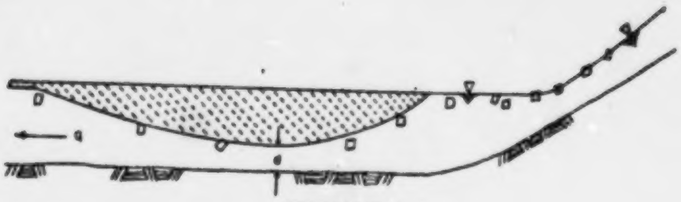


FIGURE 1

Process of formation of the ridge. (Pariset, Gagnon, 1967)

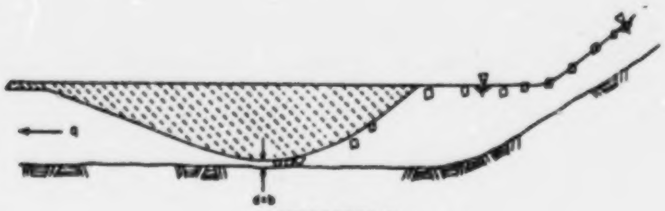


FIGURE 2

Coincidence of ice floes between the ridge and the bed.
(Pariset, Gagnon, 1967)

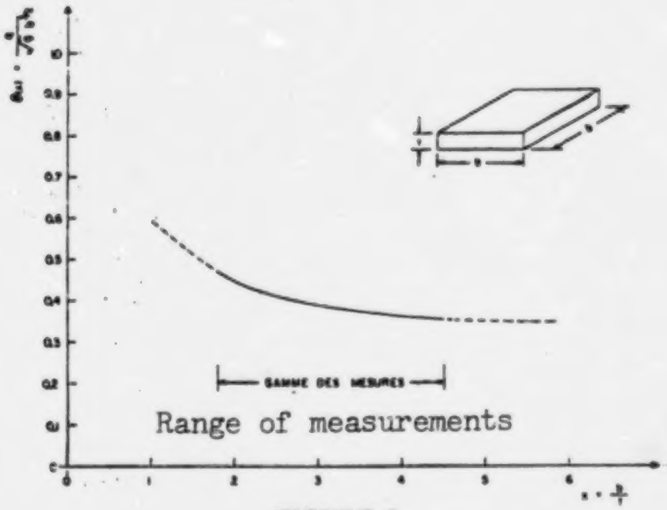


FIGURE 3

Experimental curve giving values of $\theta(x)$. (Pariset, Gagnon, 1967) magnitude of the large dimensions of the ice blocks which continue to appear, there is a risk of blockage by joining or fussion of the ice floes between the cover and the river bed. This situation is shown in figure 2. By repetition of this phenomenon and accumulation of the ice floes which follow, the ice pack can anchor itself solidly by accreation to the ice dam on the river channel and this occurs in a zone where at the outset the formation of the ice cover was effected without hinderance.

"Theory summary

"Imagine that the blocks of ice are square parallelepipeds of side 'b', thickness 't' and defined by

$$x = \frac{b}{t}$$

"An ice floe under the ice dam is subjected to the hydrodynamic force

$$C_o \rho A \frac{u^2}{2}$$

where C_o is a velocity coefficient,
ρ is the fluid density,
A is the effective area blocking the flow
u is the velocity of the fluid.

"The effective area of the block can be represented by:

$$C' b^2$$

C' will be a coefficient of form ('coefficient de forme'), of the sort which the application on the block becomes

$$C \rho b^2 u^2/2$$

then posing $C = C_o C'$.

"The other part, the resistance to movement of the block is:

$$g\ (\rho - \rho')\,\frac{b^3}{x}\tan\phi$$

where ρ' is the density of the block
ϕ is the angle of internal friction of the accumulation of ice in the dam.

"When the stream velocity equals the velocity of displacement u_a, one has an equilibrium, such that:

$$C\rho\ b^2\,\frac{{}^{u}a^2}{2} = g\ (\rho - \rho')\,\frac{b^3}{x}\tan\phi$$

where $u_* = \left(\frac{\tan\phi\ \ (\rho - \rho')}{C\qquad x\,\rho}\right)^{\frac{1}{2}}\ \sqrt{g}\ b$

The other part, the release 'd' under the ice cover corresponds to

$$d = \frac{\varphi}{u_*}$$

where φ is the loss by filling the width.

"The blocks risk fusing themselves when the release is on the order of magnitude of the ice blocks such that: $d\ \eta\ d$, of leaving which the last two equations indicate that energy or velocity which will avoid their fusion, it is necessary that

$$\varphi > \sqrt{\frac{\tan\Phi\ \ (\rho - \rho')}{C\ \ x\qquad \rho}}\ \sqrt{g}\ b^{3/2}$$

where

$$\varphi > \Theta\ (x)\ \sqrt{g}\ b^{3/2}$$

with

$$\Theta (x) = \sqrt{\frac{\tan \Phi}{C \; x}} \frac{\rho - \rho'}{\rho}$$

$\Theta (x)$ is a dependent function of x, that is to say, the agreement b/t.

"Since tan Φ , and C are the unknowns which probably depend on x, a series of experiments have permitted the determination of the values of $\Theta (x)$ for a certain range of variation of the parameter x.

"Experimental determination of the parameter $\Theta (x)$

"An experimental model in a plexiglass flume permitted us to make several measurements before determining the order of magnitude of the unknown parameter."

The result indicated "... that the parameter varied little and could be replaced by a constant equal to 0.4. (fig. 3)."

The paper is concluded by descriptions of model studies and comparisons to actual ice jams on the St. Lawrence River. Some limitations of the study were: 1) an accumulation of drifting floes can cause jams but was not investigated; 2) the configuaration of the model ice introduced simplifications to the study, but also gave a "good statistical representation;" and 3) the "concept of loss by filling the width is more reasonable for a narrow river".

Cartier (1960) describes the results on one season of tests on the same experimental canal that Pariset and Hausser used in their tests. Naturally formed ice was utilized under weather conditions representing areas where the results would be applied.

"The experiments of this first season on these aspects of ice cover formation, progression and breaking lead to the following preliminary results and conclusions.

1) Formation of an ice cover.

a) For given ice inflows the rate of upstream progression of the cover is maximum for flow velocities under 1.5 feet per second. For higher flow velocities, up to 2 feet per second, part of the incoming ice is carried underneath and consequently the rate of upstream advancement diminishes.

b) For flow velocities between 2.0 and 2.2 feet per second, the cover still advances upstream but with much difficulty, most of the incoming ice being entrained under the progressing cover and it appears that only under special circumstances will an ice cover pack upstream for higher flow velocities. Tests on overturning of ice blocks confirm the upper limit by the mean value of 2.30 feet per second obtained for the velocity causing overturning.

c) Tests results also indicate that an already established ice cover will be dislocated at its upstream edge when the surface velocity of the water reaches approximately 3 feet per second, the range in values obtained from the tests being from 2.5 to 3.8 feet per second. The covers had thicknesses of some 6 inches....

2) Overturning of ice blocks

"Velocities obtained ranged between 1.6 and 3.2 feet per second... and these values substantiate in the range observed the results obtained in the laboratory, correlating closely with theoretical analysis and laboratory experimentation."

Morton (1963) investigated the stability of a packed ice cover using the early research of Pariset and Hausser (1961). A large portion of the report is omitted here for that reason. However, the following significant differences are listed by the author:

"a) The subject matter is limited to the problem of stability of packed ice cover.

b) The mathematical model is extended to take into account the effects of variations in the roughness of the underside of the ice cover.

c) The state of incipient instability for a packed ice cover is defined in mathematical terms."

"The principal assumptions used in the development of the theory are as follows:

a) The river channel is regular in shape and alignment.

b) A packed ice cover near a state of incipient instability has no internal cohesion.

c) Pavlovskii's solution of Manning's formula may be used to derive head losses and shearing forces under the ice cover."

"Relationship between velocity and thickness

"It is evident from inspection of Plate 1 that the transition between a narrow and a wide ice cover, for the conditions of channel and ice roughness specified, occurs when

$$\frac{D^{2/3}}{B^{1/2}}$$

is slightly more than one quarter. However, such a ratio would be much larger for rougher ice covers. In an attempt to provide an approximate general expression for transition between narrow and wide ice covers, it is specified that such a transition occurs when the ratio

$$\frac{V}{(2gD)^{1/2}}$$

for both types of covers are equal at a relative thickness of one third, since at this relative thickness the variation in the ratio is small. Plate 2 has been prepared by application of this specification to the relevant equations and shows for a channel with a Manning roughness coefficient of 0.030, the transitional width between narrow and wide covers as a function of channel depth and the Manning roughness coefficient for the underside of the ice cover. The plate shows that the transitional width for constant depth is increased by a factor of 8 when the roughness coefficient for the underside of the ice cover decreases from 0.060 to 0.012. It also shows that most natural channels on which ice forms by packing would fall into the wide category even when the ice cover is very smooth.

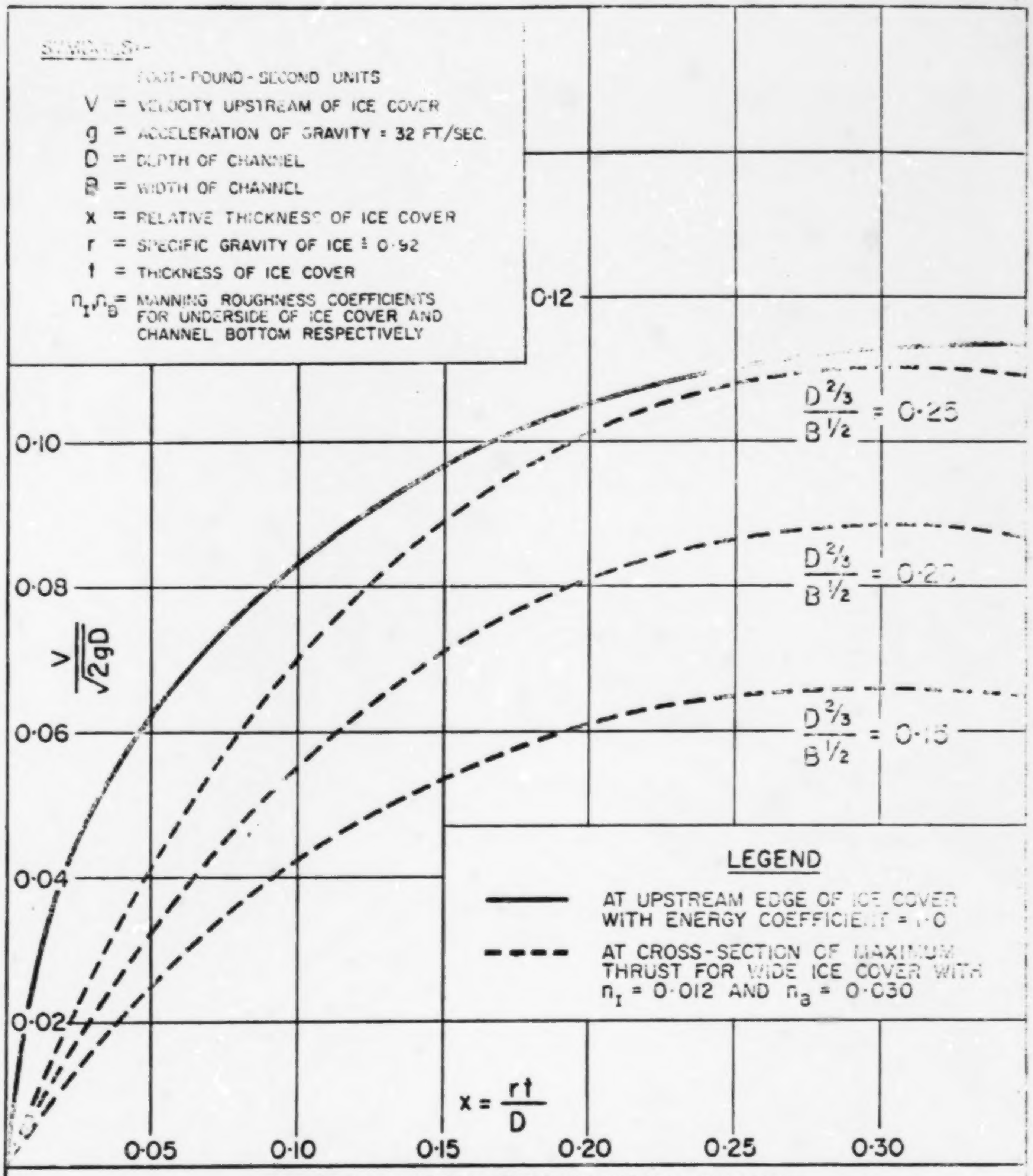
"The shape of the curves for wide ice covers on Plate 1 may be explained as follows:

a) For any particular velocity upstream of the ice cover assumes a thickness sufficient to withstand the resultant thrust.

b) If the velocity upstream of the cover should increase, the thrust would increase and the cover would thicken. However, the process of thickening, by constricting the flow, increases the thrust still further. Therefore, the rate of change of thickening with respect to velocity increases with increased thickness.

c) When the cover reaches a certain critical thickness, the increased thrust due to thickening exceeds the increased strength due to thickening. Theoretically the ice cover would then thicken down to the bottom of the channel, completely blocking it. Under natural conditions complete blockage is rare since partial blockage tends to increase the water levels in the channel and upstream, thus reducing the

PLATE 1



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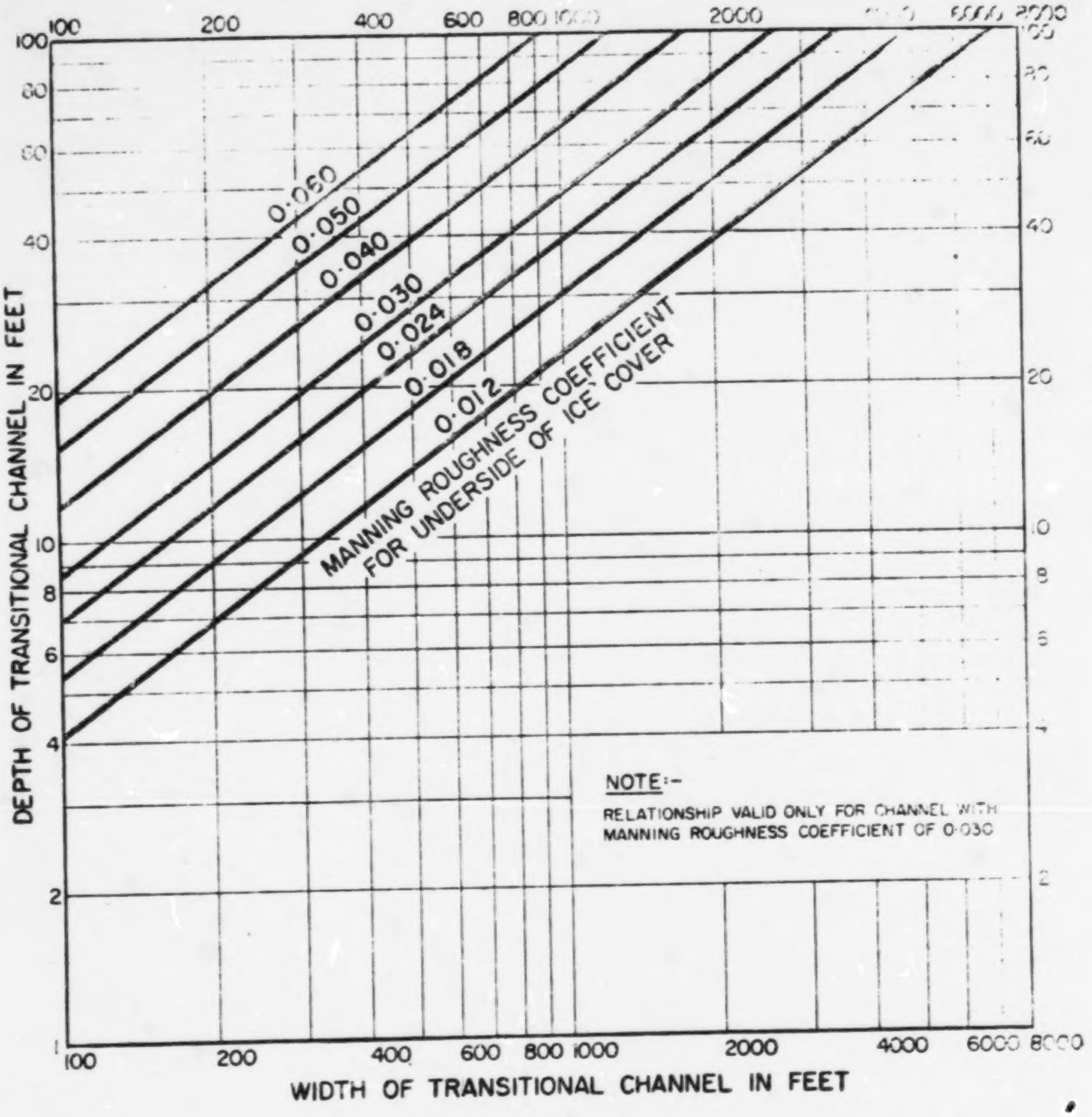
CRITERIA FOR THE STABILITY OF ICE COVERS ON RIVERS

RELATIONSHIP BETWEEN VELOCITY UPSTREAM OF ICE COVER AND THICKNESS OF ICE COVER (Morton, 1963)

PLATE 2



NOTE:-

RELATIONSHIP VALID ONLY FOR CHANNEL WITH MANNING ROUGHNESS COEFFICIENT OF 0·030

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CRITERIA FOR THE STABILITY OF ICE COVERS ON RIVERS

TRANSITION BETWEEN NARROW AND WIDE COVERS
(Morton, 1963)

velocity and permitting a new state of equilibrium to be reached. This... is discussed in a subsequent section entitled 'Hanging Dams'. The process of complete or partial blockage after an ice cover becomes unstable is referred to as jamming.

d) The jamming velocity and the jamming relative thickness prevail at a time the jam is initiated. They may be noted on the curves on Plate 1 at the points where the rate of change of velocity with respect to thickness is zero.

"The explanation of the shape of the curve for narrow ice covers is similar. However, when the critical thickness is reached, the front end of the cover submerges and breaks off to lodge further downstream. The process is referred to as submergence.

"The submerging or jamming relative thickness may be derived by differentiating the expression for velocity upstream of the ice cover with respect to the relative thickness and setting the result equal to zero. For a narrow ice cover, the submerging relative thickness is constant 0.333. However, the jamming relative thickness for a wide ice cover depends on the ratio of the Manning roughness coefficient for channel bottom to the Manning roughness coefficient for underside of ice cover n_B/n_I. It can decrease from 0.36 to 0.29 as the roughness ratio increases from 0.5 to 3.3.

"Submerging velocity

"The submerging velocity for narrow ice covers may be derived by introducting the value of 0.333 for the submerging relative thickness into the expression for velocity. If the energy coefficient and specific gravity of ice are assumed to be 1.00 and 0.92 respectively, the criterion for stability of an ice cover reduces to

$$V_{CO}=0.113\ (2gD)^{1/2}$$

where V_{CO} is the submerging velocity upstream of ice cover. In practice, the value of 0.113 should be reduced to 0.1 to allow for the possibility that the energy coefficient may be as high as 1.3 or 1.4.

"The expression in the foregoing paragraph shows that the stability of a narrow ice cover is dependent only on the velocity of flow upstream of the ice cover and the depth of channel. However, wide ice covers are much more common than narrow ones and their stability requirements are more stringent. All further discussion of stability of packed ice in this paper is confined to wide ice covers.

"Jamming velocity

"The jamming velocity for wide ice covers may be derived by introducing the jamming relative thickness into the expression for velocity. Plate 3 supplies a general solution to the problem by showing

$$\frac{V_{CZ}}{1.49} \left(u \frac{1-r}{r} \quad \frac{D^{7/3}}{B} \right)^{-1/2}$$

as a function of the Manning roughness coefficient for underside of ice cover (n_I) and for channel bottom (n_B), where V_{CZ} is the jamming velocity.... It should be noted that the relationship on Plate 3 is not dimensionless.

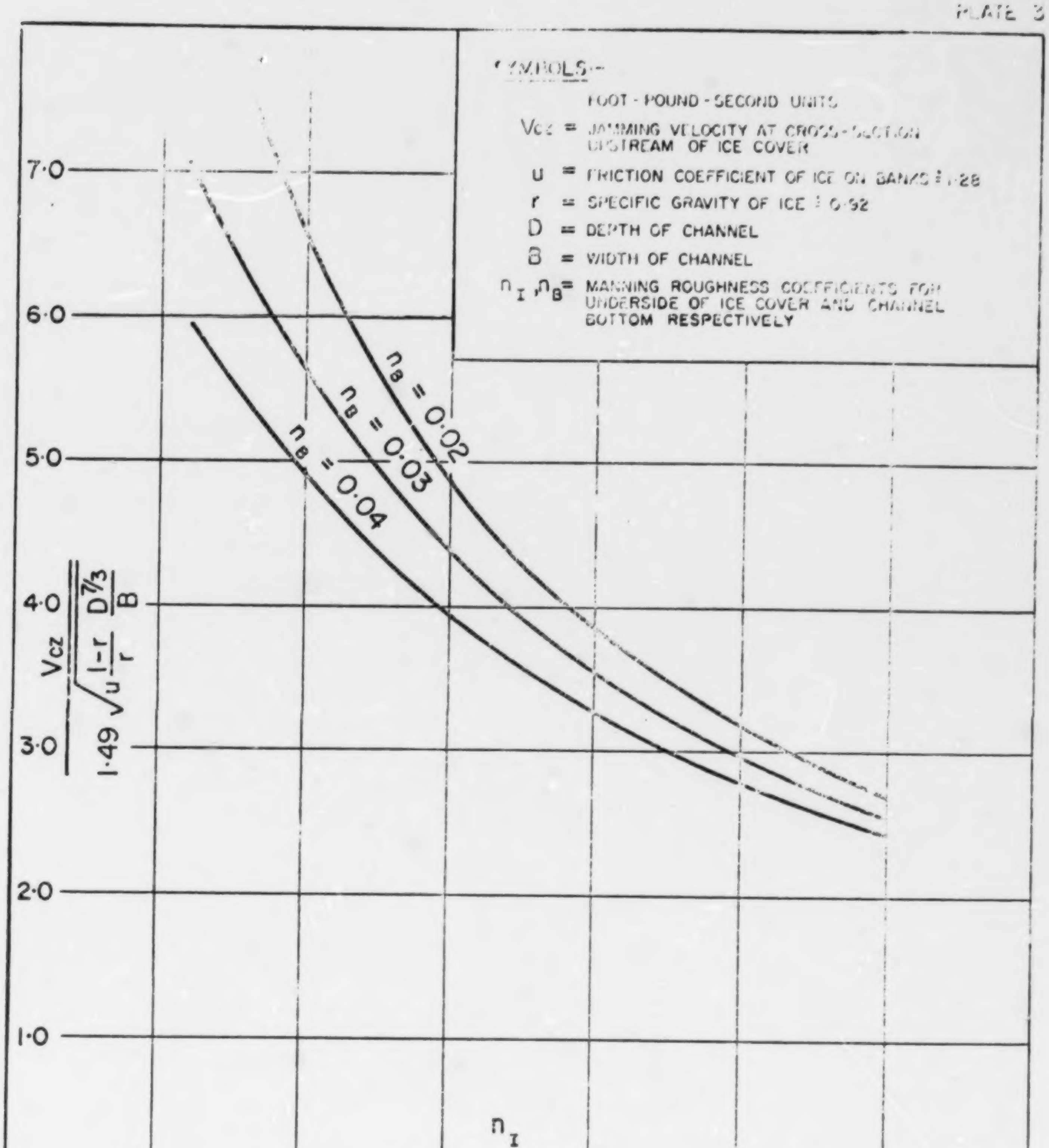
"It is evident from Plate 3 that the jamming velocity increases very rapidly with a decrease in the Manning roughness coefficient for the underside of the ice cover. Very little is known about this coefficient, but it is conceivable that it could vary from as hign as 0.06 to as low as 0.012 in a yearly progression from newly formed roughness to ultimate smoothness. With such a progression, the capacity of the ice-covered channel during formation of the cover would be only 25 to 40 percent of the capacity some time after formation.

"Plate 3 also shows that the jamming velocity decreases with increased roughness of the channel bottom. However, it is not nearly as sensitive to this roughness as to the roughness of the ice cover.

"Plate 4 has been prepared from the curves on Plate 3 to show the relationship between the jamming velocity and the roughness of the ice cover for a channel with a width of 3,000 feet, a depth of 30 feet, and roughness coefficient of 0.030. It is evident that, for such a channel, the jamming velocity possibly may vary from 1.2 feet per second to 3.4 feet per second as the bottom of the ice cover smoothed out after a very severe formation process.

"Pariset and Hausser (1961) assumed that the roughness of the underside of the ice cover is the same as the roughness of the channel bottom, and the use of this assumption provided a relationship which agreed quite well with ice thickness measurements in the Beauharnois Canal and St. Lawrence River. For the particular channel of Plate 4, such an assumption would provide a value for jamming velocity of 2.1 feet per second, which is reasonably close to the 2.25 feet per second recommended by the Joint Board of Engineers in 1926 (1927) and subsequently employed in the design of channel enlargements in the International Rapids Section of the St. Lawrence River.

"It is evident from an inspection of Plate 3 and 4 that the selection of a cross-sectional area in the design of channel enlargements to permit



DEPARTMENT OF NORTHERN AFFAIRS AND NATIONAL RESOURCES
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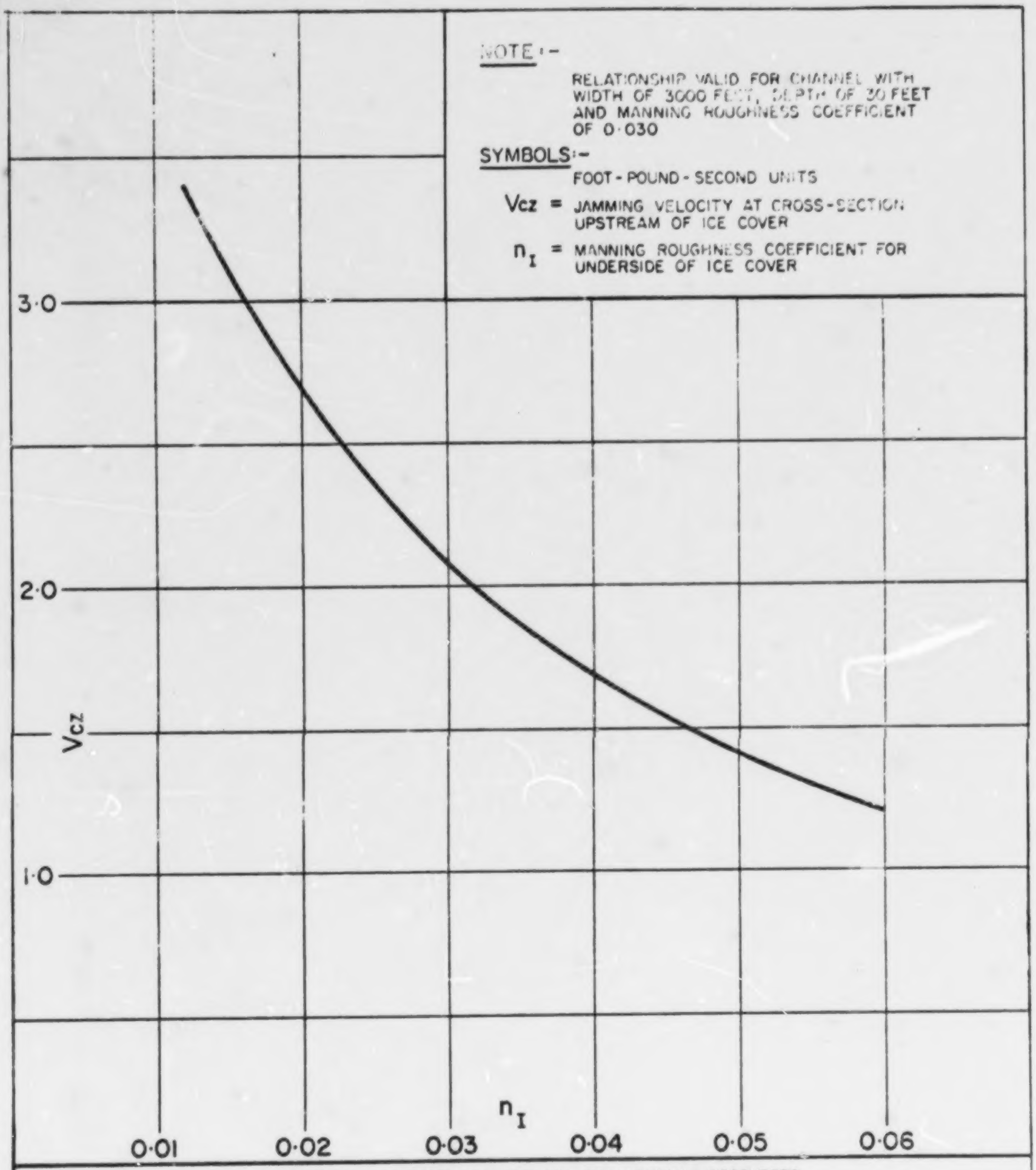
CRITERIA FOR THE STABILITY OF ICE COVERS ON RIVERS

GENERAL RELATIONSHIP BETWEEN
JAMMING VELOCITY AND ROUGHNESS COEFFICIENTS
(FOR WIDE ICE COVER) (Morton, 1963)

PLATE 4



NOTE:-

RELATIONSHIP VALID FOR CHANNEL WITH WIDTH OF 3000 FEET, DEPTH OF 30 FEET AND MANNING ROUGHNESS COEFFICIENT OF 0·030

SYMBOLS:-

FOOT-POUND-SECOND UNITS

Vcz = JAMMING VELOCITY AT CROSS-SECTION UPSTREAM OF ICE COVER

n_I = MANNING ROUGHNESS COEFFICIENT FOR UNDERSIDE OF ICE COVER

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CRITERIA FOR THE STABILITY OF ICE COVERS ON RIVERS

SPECIFIC RELATIONSHIP BETWEEN JAMMING VELOCITY AND ROUGHNESS COEFFICIENT (FOR WIDE ICE COVER) (Morton, 1963) the formation of a stable packed ice cover is dependent on the assumption of a value for the maximum roughness of the underside of the ice cover.... The accumulation of such data will be a long drawn out process, since, because of the danger of making ice thickness measurements on a newly-packed ice cover, it must be obtained by the analysis of well-documented ice jams.

"The equation relating jamming velocity to channel dimensions and roughness coefficients provides a theoretical indication of the relative efficiency of channel deepening and channel widening....

"The equation for jamming velocity also shows that the construction of longitudinal dykes in a channel can increase the discharge capacity under ice-packing conditions by increasing the jamming velocity....

"Since the resultant of forces for a wide ice cover increases with distance from the upstream edge, it might appear as though the capacity of the channel could be increased by the installation of transverse ice booms, which would absorb the thrust of ice before the maximum value is attained. However such booms would have to be numerous and extremely strong. For example, transverse ice booms, spaced every 1500 feet across a channel 3000 feet wide and 30 feet deep, would increase the capacity by less than 20 percent and would require sufficient strength to resist a thrust of 200 to 300 pounds per foot of channel width.

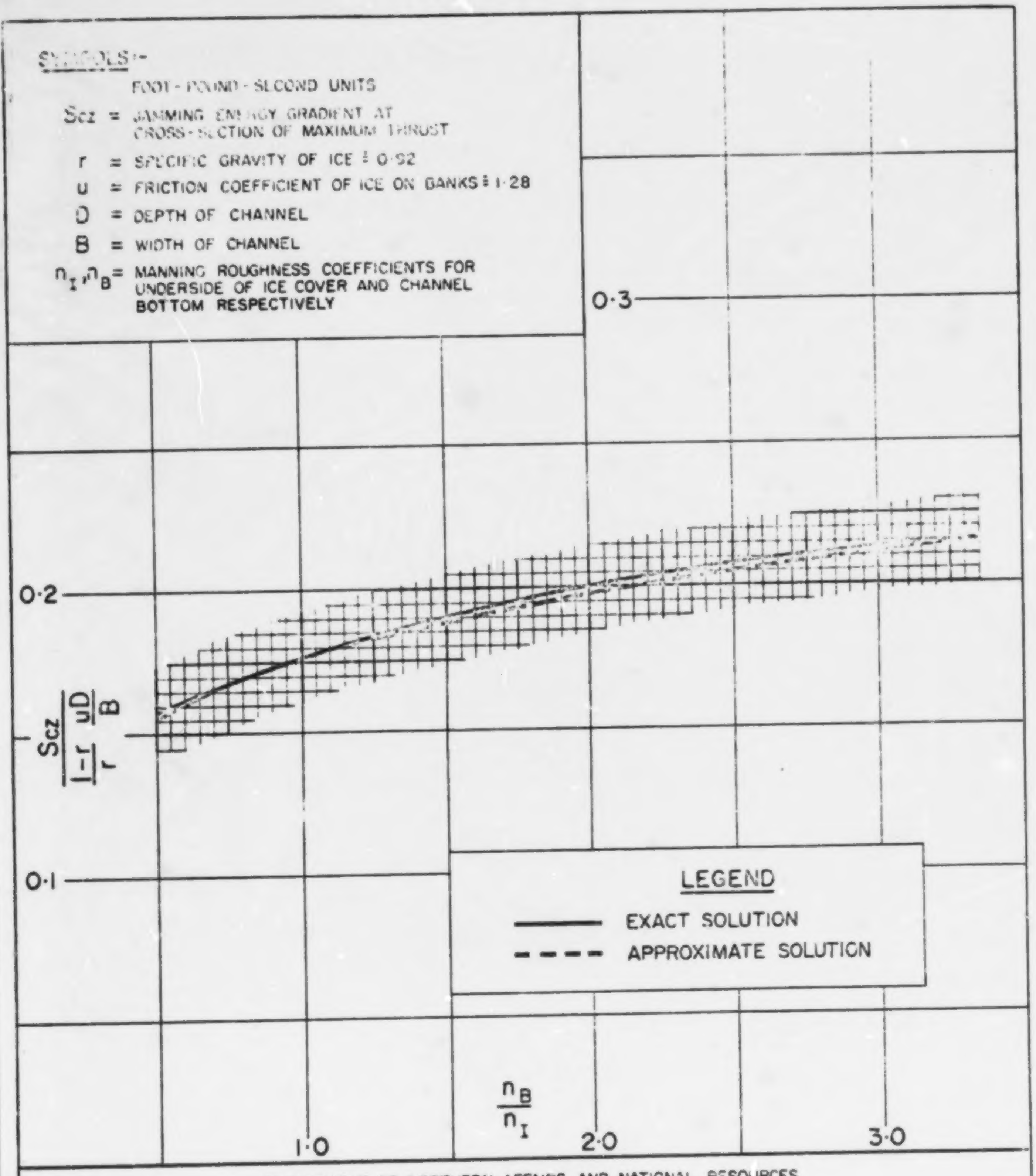
"Plates 4 and 5 have implications for the operation of storage or diversions to form or retain packed ice covers. They show that the reduction of the roughness of the underside of the ice cover subsequent to packing may result in an increase in channel capacity of well over 100 percent. However, increases in flow of this magnitude require a more reliable stability criterion than the jamming velocity, since neither the initial nor final roughnesses are known. In the development of the equations for jamming velocity, it became apparent that the energy gradient under an ice cover in a state of incipient instability provides such a criterion since it can be measured and since it is very insensitive to changes in roughness....

"Jamming energy gradient

"A relationship between the energy gradient under the ice cover and the relative thickness of the ice cover at the cross-section of maximum thrust may be derived by equating the maximum thrust (expressed in terms of energy gradient) and the reaction strength of the cover. The jamming energy gradient at the cross-section of maximum thrust is then determined by introducting the jamming relative thickness into this relationship. Plate 5 shows

$$S_{CZ} \ \left(\frac{1-r}{r} \quad \frac{uD}{B}\right)^{-1}$$

PLATE 5



SYMBOLS:-

FOOT-POUND-SECOND UNITS

S_{cz} = JAMMING ENERGY GRADIENT AT CROSS-SECTION OF MAXIMUM THRUST

r = SPECIFIC GRAVITY OF ICE ≑ 0·92

u = FRICTION COEFFICIENT OF ICE ON BANKS ≑ 1·28

D = DEPTH OF CHANNEL

B = WIDTH OF CHANNEL

n_I, n_B = MANNING ROUGHNESS COEFFICIENTS FOR UNDERSIDE OF ICE COVER AND CHANNEL BOTTOM RESPECTIVELY

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CRITERIA FOR THE STABILITY OF ICE COVERS ON RIVERS

GENERAL RELATIONSHIP BETWEEN
JAMMING ENERGY GRADIENT AT CROSS-SECTION OF
MAXIMUM THRUST AND ROUGHNESS COEFFICIENTS
(FOR WIDE ICE COVER) (Morton, 1963)

as a function of the roughness ratio n_B/n_I, where S_{CZ} is the jamming energy gradient at the cross-section of maximum thrust and all other symbols are as previously defined. The solid line is the exact solution, and the broken line is an approximate solution relating the jamming energy gradient to the one-sixth power of the roughness ratio....

"The jamming energy gradient is very insensitive to changes in the roughness of the underside of the ice cover....

"The jamming energy gradient shown on Plate 5 has the operational disadvantage of existing only at the cross-section of maximum thrust. Plate 6 shows the ratio S_{CL}/S_{CZ} as a function of the roughness ratio n_B/n_I, and the ratio $2uL/B$, where S_{CL} is the jamming energy gradient at distance L from the upstream edge of the cover... Plate 6 permits the computation of an average value of jamming energy gradient between two water level gauges, each located on the plate in accordance with the ratio of distance from the upstream edge of the cover to channel width....

"The stability of hanging dams is beyond the scope of this paper. The equations for packed ice covers are not strictly applicable since they do not include the effects of the non-frictional head losses and the velocity head changes which assume some importance when the ice cover is very thick. However they can be used to illustrate, in an approximate and general manner, the stability requirements for hanging dams."

Using field measurements of an ice jam on the St. Lawrence River, Morton found only a 3% variation in the theoretical and actual jamming energy gradients. "However this excellent agreement does not provide a decisive check on the theory because of the large amount of judgment required in the interpretation of the data."

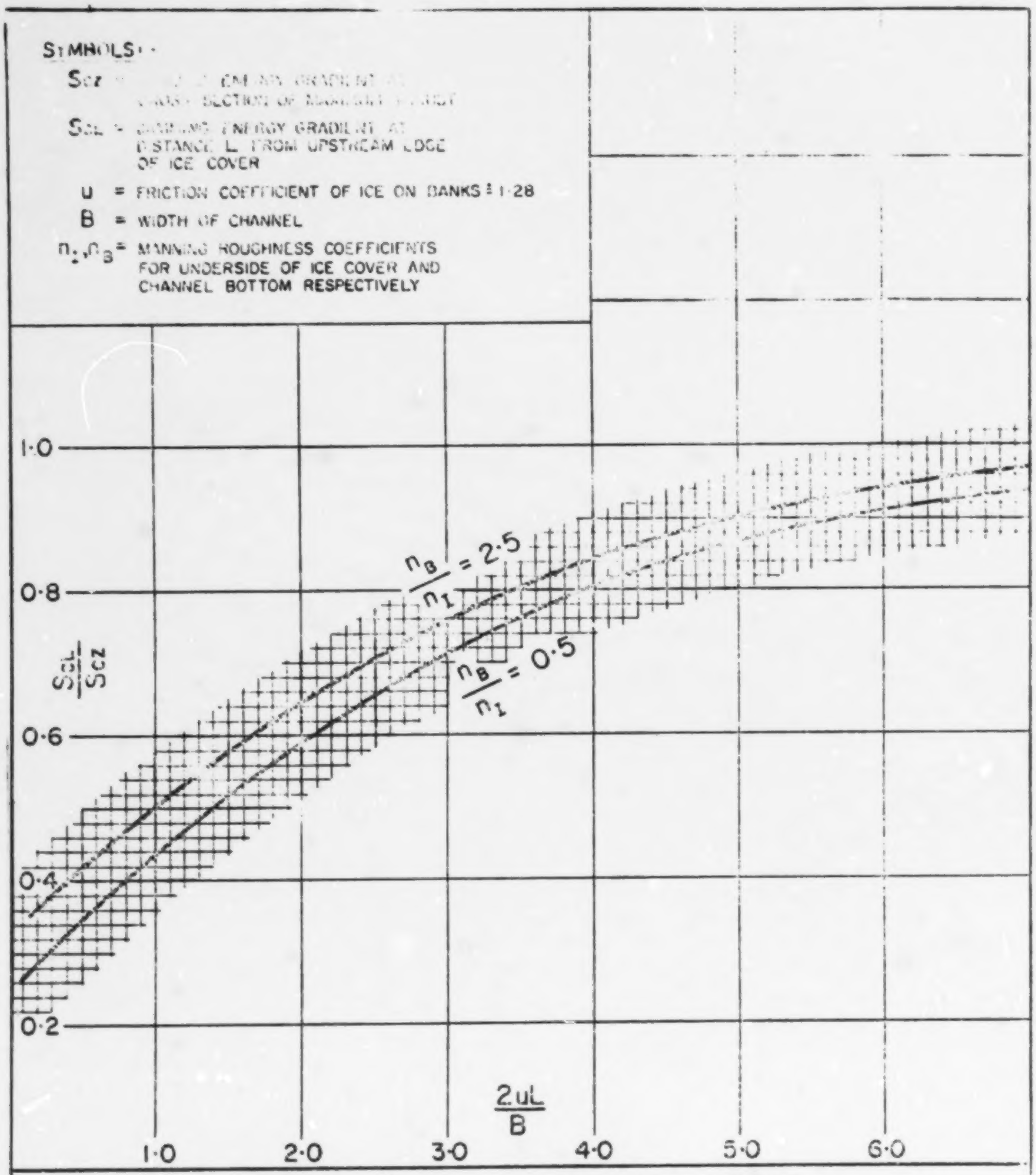
Some indication of the ice jamming mechanism controversy is given in the comments of Pariset and Hausser (1963) on Morton's paper.

"Most important is the fact that the carrying of ice under the cover, by flow, plays a very important part long before the cover can attain such a thickness....

"If in wide rivers and at low velocities, thickening of the ice cover is governed by the phenomena studied by Mr. Morton, observations and calculations show that as the flow velocity increases, an increasing percentage of incoming ice floes, instead of packing against the cover, are carried and partly deposited under the cover. Such deposits thicken the ice cover until a new equilibrium is reached; all incoming floes are carried under the cover and travel downstream....

"We found that the main parameter governing ice jam formation was the discharge of ice coming from upstream. The equation governing the maximum thickness of the cover to obtain stability was used as a control but in fact was rarely the governing factor....

PLATE 6


SYMBOLS:-

S_{cz} = JAMMING ENERGY GRADIENT AT CROSS-SECTION OF MAXIMUM THRUST

S_{cL} = JAMMING ENERGY GRADIENT AT DISTANCE L FROM UPSTREAM EDGE OF ICE COVER

u = FRICTION COEFFICIENT OF ICE ON BANKS ≐ 1·28

B = WIDTH OF CHANNEL

n_I, n_B = MANNING ROUGHNESS COEFFICIENTS FOR UNDERSIDE OF ICE COVER AND CHANNEL BOTTOM RESPECTIVELY

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CRITERIA FOR THE STABILITY OF ICE COVERS ON RIVERS

VARIATION OF JAMMING ENERGY GRADIENT WITH DISTANCE FROM UPSTREAM EDGE OF WIDE ICE COVER

(Morton, 1963)

"We agree with Mr. Morton that the flow velocity cannot be taken as a criterion for ice cover stability, as the critical velocity depends not only on meteorological conditions, but also upon the depth of the water, the shape and roughness of the bed, the discharge of ice coming from upstream, etc... In fact we used it only as a classifying parameter to explain the various phenomena....

"Introduction of the effects of variation in the roughness of the underside of the ice cover may be useful....

"Pavlovsky and Belokoni (in Levi, 1948) propose, from a large number of field measurements made in Russia, the following mean variation of the roughness coefficient:

After formation of the ice cover	With Frazil	Without Frazil
First 10 days	0,150	0,050
10 to 20 days	0,100	0,040
20 to 60 days	0,050	0,030
60 to 80 days	0,040	0,025
80 to 100 days	0,030	0,015

"Our study of the St. Lawrence River was based on measurements taken by Hydroelectric Commission of Quebec. From these measurements it would seem that on the St. Lawrence the roughness of the underside of the ice cover becomes, after a few days, approximately the same as the river bed. However, it can be noticed that during the formation of the ice jam in the Montreal Harbor, the upstream water level goes up quickly and down slowly after the formation of the ice jam. This is due either to a smoothing effect of the ice or to an erosion of the underside of the ice cover which could appear after the formation of ice jam.

"Plate 1 - The dotted curves corresponding to the cross section of maximum thrust depend not only upon the roughness coefficient of the bed and ice cover, and of the cross section of the river, but also upon the shape of its layout. Calculations show that a larger thickening occurs in a divergence of the river as less thrust is transmitted to banks; the opposite being true to a convergence....

"Plate 2 - Using the results of Plate 2 to differentiate between wide and narrow rivers applies only when ice cover thickness reaches the thickness corresponding to maximum thrust it can sustain, not from the beginning of ice cover formation, as does the criterion we have used.

"Plates 3 and 4 - Show quite clearly that velocity cannot be taken as a criterion for stability but only as a classifying parameter to describe what is happening. On the St. Lawrence, downstream of Montreal, experience has shown that the bed and the ice roughness are practically equal, but of course the ice cover is much thinner than the case for which Mr. Morton's calculations apply. We do not consider plate 4 as a possible justification of the recommendation to adopt V = 2,25 since the formation on the St. Lawrence of such a thick ice cover would considerably increase the loss of head and cause disastrous flooding.

"Jamming energy gradient

"The jamming energy gradient, insensitive to changes in roughness of the underside of the ice cover, may be useful in some cases as it gives the limits of head losses before inducing large ice jams.

"However, this criterion does not seem practical in designing a channel which has to pass a given discharge, or to determine the maximum possible discharge in an existing channel. The determination of these characteristics requires indeed the use of velocity loss of head formula which depends upon the roughness of the bed and of the underside of the ice cover....

"Plate 6 - We cannot agree with calculations leading to plate 6 because the application of theory along a reach of the river must take into account the loss of head and so imply a back-water calculation."

Michel (1965) analyzes the mechanism of ice jam formation and defines the "soft" ice jam.

"The locks and the ice jams

"When the concentrated quantity of ice floes encounters a local obstacle and is halted, there is a lock or ice jam. If the quantity of ice is considerable, these masses are called ice jams in the local language.

"The obstacle can be: - a continuous ice field, very thick and resistant - an irregularity of the bed (narrowing, shoal, island, pronounced curve, ect.).

"In many of the cases, it is necessary that the site possess an attraction for the formation of an ice jam, that is to say, in nature, a continuous ice field from one bank to the other. The obstacle now temporarily stops the passage of the ice floes. These accumulate and the water level upstream rises.

"The Laws of Equilibrium of Locks

"Equilibrium of the leading edge of the lock

"This condition of stability is similar to the conditions of freezing of an ice field, only if the ice floes are well defined and rather regular.

"For square blocks where the thickness is 1/4 of the length, the leading edge is stable when...

$$Fr \leq 0.12 \tag{1}$$

Fr - the Froude number in front of the lock. This condition can also be written:

$$q \leq 0.68\, h^{3/2} \tag{2}$$

q - discharge per unit area of flow in cfs/ft,
h - depth of water (flow width) in front of the lock in ft.

"Equilibrium of the lock under the effect of pressure

"The flow exerts tangential forces under the lock, which are attached to the weight of the accumulated ice. These forces are distributed in the interior of the accumulation and the thickness of which can be adjusted for resisting these forces.

"In the case of a uniform flow and an ice field of constant thickness, the thickness can attain its maximum at a distance approximately equal to 5 or 6 times the width of the flow. From the theory of Caquot, for silos, one can calculate the equilibrium of the thickness for the ice accumulation (see annex). The results are indicated in figure 3 which shows, in relative values, the requisite thickness as a function of the water depth. This curve also shows that the cover resists pressure such that:

$$h \leq 2.36\mu \frac{\sqrt{Q}}{\sqrt[4]{B}} \tag{3}$$

Q - flow discharge in cfs,
B - width of flow in ft,
μ - a coefficient depending on the internal friction of the ice floes, the porosity of the floes and the coefficient of flow friction.

"The difficulty of using this criterion lies in the choice of the value of the coefficient μ. For a value $\text{tg}\,\phi$ of the internal friction 0.1 to 0.5, it varies from 0.51 to 0.26. Experiments with blocks of

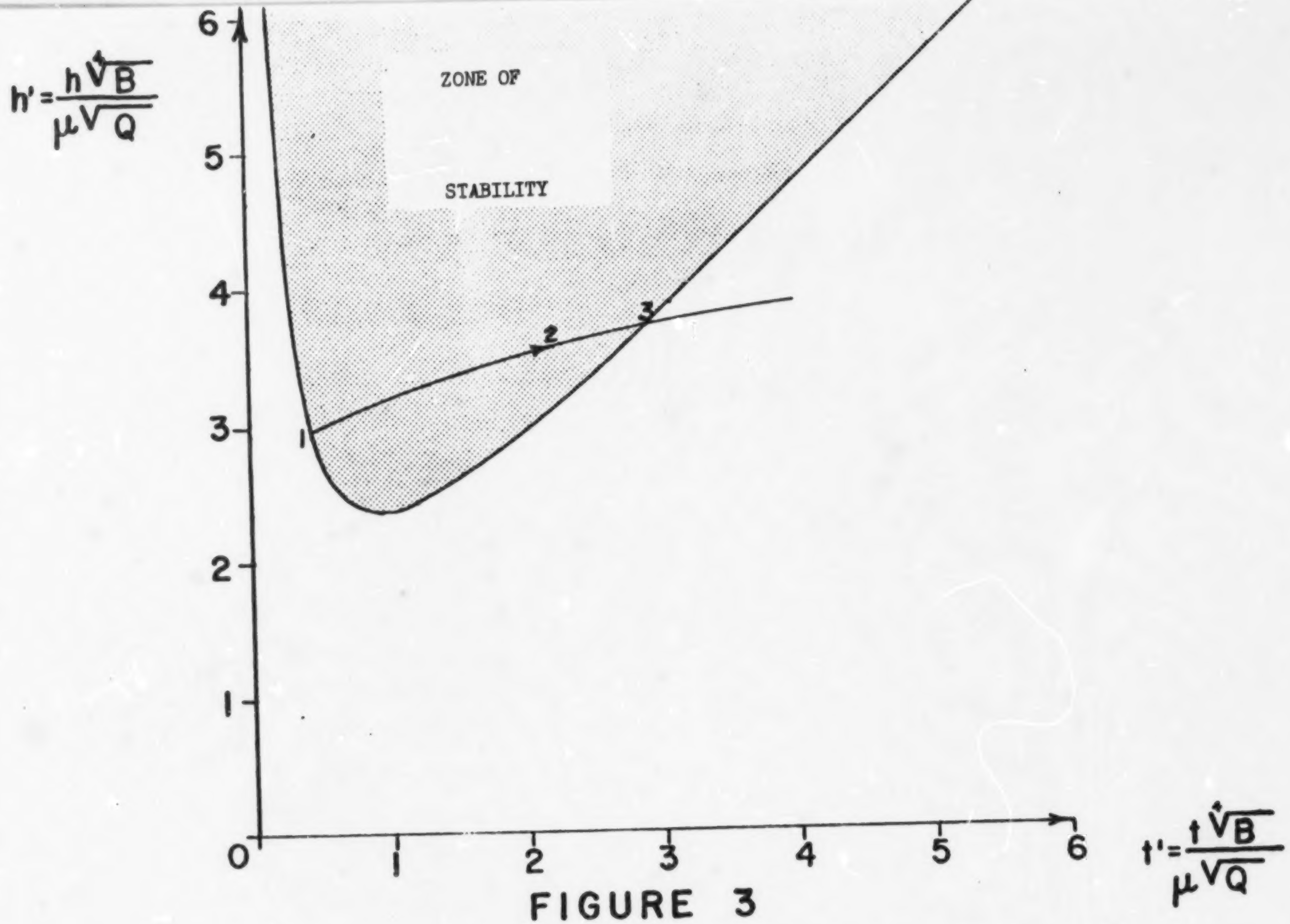


FIGURE 3

EQUILIBRIUM OF LOCKS UNDER THE EFFECT OF PRESSURE (Michel, 1965) polyethylene, in the laboratory give a coefficient of 0.26. Another part of the internal friction of the ice cannot be superior to that of the polyethylene and that value of $\mu = 0.26$ is most certainly safe for the calculations of ice jams.

"In adopting this value, one now finds that the lock will be stable when:

$$q \leq \frac{2.67\ h^2}{\sqrt{B}} \qquad (4)$$

"Equilibrium of the lock under the influence of drag

"If the flow velocity beneath the lock attains and passes the critical velocity for the start of drag the ice floes will be carried downstream and that can destroy the whole lock.

"A good approximation of the value of this velocity can be obtained by analogy, for blocks whose surface dimensions are four times the thickness, and which travel beneath an accumulation of blocks of the same form. This gives:

$$V_c \leq 10\sqrt{D} \qquad (5)$$

where: V_c - velocity limit of start of drag in ft/sec,
D - thickness of the ice floes in ft.

"With the same preceding variables and for ice floes two feet thick, this relation becomes:

$$q \leq 14\ (h - t) \qquad (6)$$

where: t- thickness of the accumulation below the water in ft.

"Predominant criterion of equilibrium of the locks

"The three preceding criteria can be represented on a graph (figure 4).

"The criterion of equilibrium at the drag velocity can never occur prior to the two others, even in the worst case where the maximum thickness

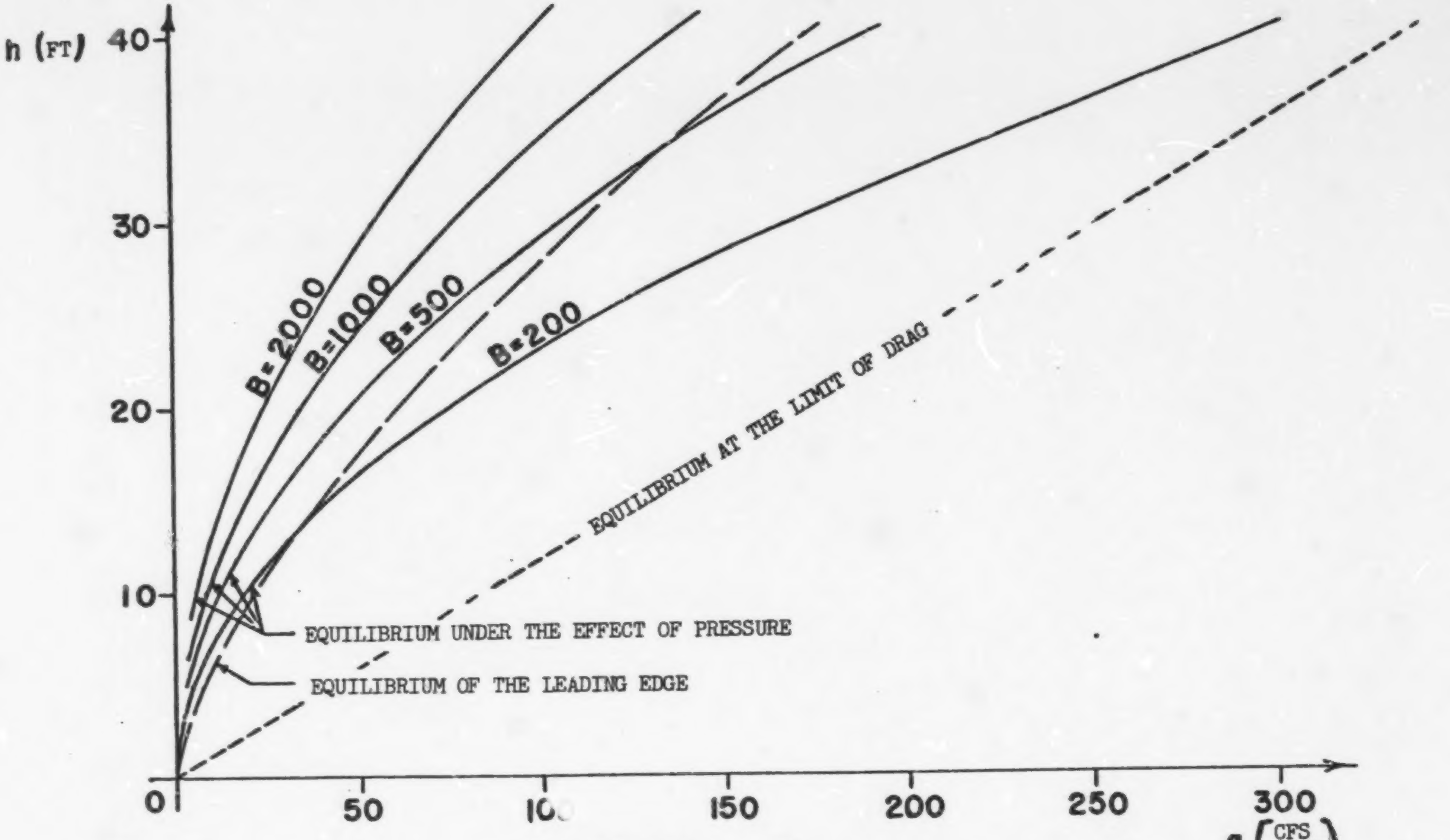


FIGURE 4

PREDOMINANT CRITERION OF EQUILIBRIUM OF LOCKS (Michel, 1965) t/h of accumulation becomes equal to 0.4, which corresponds to fracturing under the effect of the pressure.

"If one holds to account the natural values of q and h for rivers, large or small one finds very generally, that the criterion determining the equilibrium of the locks is that of pressure. Even if the coefficient μ of the accumulated ice is over 0.26, this only accentuates the predominance of this criterion upon it of the frontal equilibrium of the lock.

"However, it is to be noted that, for small rivers, the initial disequilibrium at the fracturing (crushing) is very rapid following the disequilibrium of the leading edge.

"The dragging of ice floes beneath the lock does not first interfere as such but it is a consequence of the fracturing. Only the smallest ice floes can travel beneath the lock when it is again stable.

"The effect of an irregularity in creating locks

"A lock will be generally stable if the criterion of fracture is not passed.

"Suppose (figure 5) a narrowing of section to facilitate the discussion. Observation in nature shows that the lock goes to yield by crushing only on a width of B' of the narrow flow in permitting the vertical walls of ice along the dotted lines.

"The equation

$$q = \frac{2.67\, h^2}{\sqrt{B}} \tag{4}$$

shows that it is necessary for a discharge well above that to disengage the lock for a width B' than for the width B. This lock is now more stable and it also will be necessary that the water level upstream remain superior, for reason of the loss of force, to crush it.

"Formation of soft ice jams

"After a wave of daily increase the discharge limit is attained, the lock can no longer resist the pressures and it is crushed. Preliminary observations, on a scale model, permitted us to conceive of the following mechanisms of formation of soft ice jams.

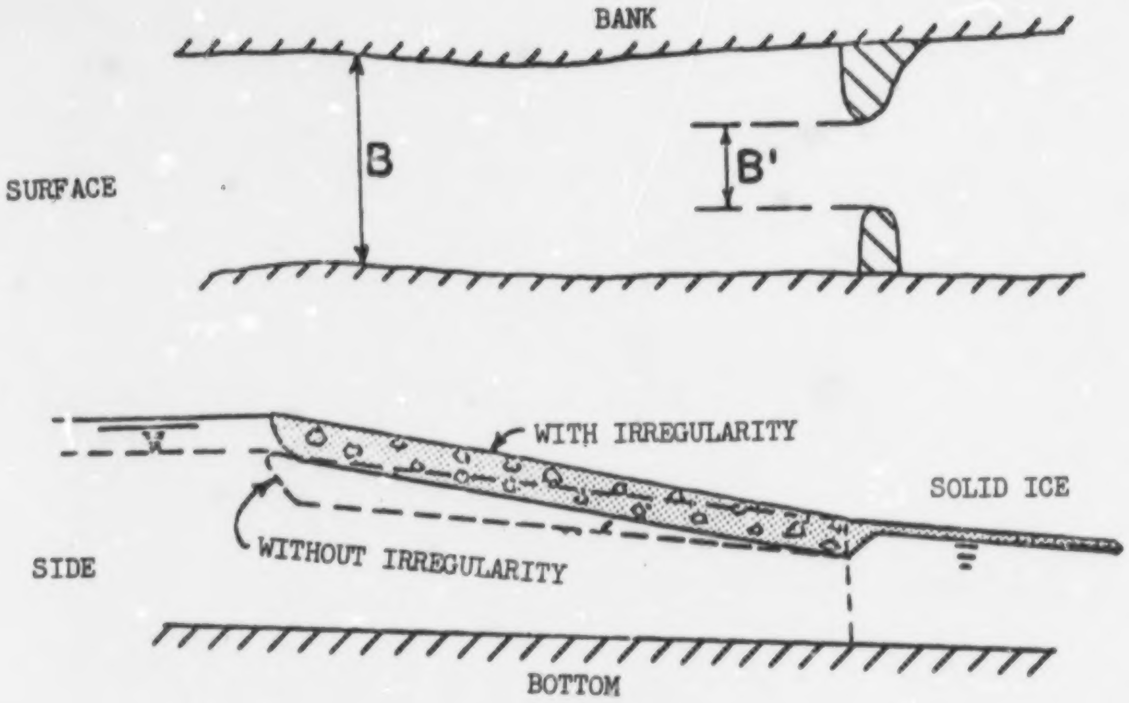

BANK
B
B'
SURFACE
WITH IRREGULARITY
SOLID ICE
WITHOUT IRREGULARITY
SIDE
BOTTOM

FIGURE 5

EFFECT OF AN IRREGULARITY UPON A LOCK (Michel, 1965)

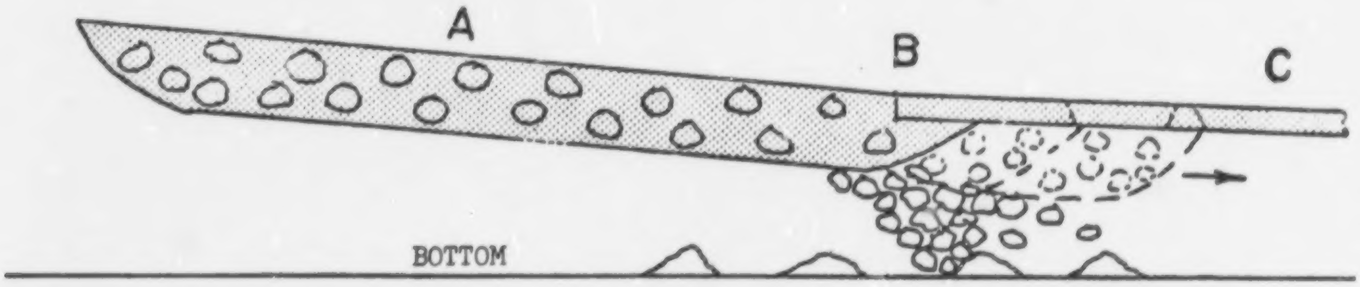


FIGURE 6

FORMATION OF A SOFT ICE JAM (Michel, 1965)

"Considering figure 6. The lock A is crushed at section B. The ice flows are carried away by the current beneath A, forming a regressive deposit under the solid cover C.

"The solid ice of C must then break under the effect of the vertical pressures of the accumulation progressing upstream.

"In certain cases one can conceive that ice floes of large size departing from B remain wedged between the uneven bottom (stream bed) of the irregularity and the lock. A stopper is formed and the soft ice jam is created, through stranding, cutting the discharge (Deslauriers, 1965)....

"A second case of soft ice jam can be produced if the discharge is considerably reduced. Suppose a lock has attained equilibrium at point 1 on figure 3 following a daily increase. During the stage which follows, the thickness of the ice remains constant and the figurative point will be displaced along 1 - 2 on the figure. If the discharge is sufficiently reduced for the trace to attain point 3, the lock becomes unstable and it will be crushed (or broken). Given the slight water depths which correspond to these conditions, the risks of cohesion and formation of a soft ice jam are increased....

"Destruction of locks and soft ice jams

"The destruction of these local accumulations can be accomplished by breaking up, by diversion of the water or simply by melting.

"The mechanism of breaking up is essentially that of crushing. In the case of a lock the ice blocks travel under the section of crushing and resume their downstream descent. In the case of a soft ice jam, the stopper must be removed at a single moment when the water level becomes sufficiently elevated upstream. In the two cases one has observed, after the event, vertical ice walls have been cut upon the banks.

"If the water level becomes sufficiently elevated upstream, before the crushing, it can happen that the water finds a new passageway in the major river bed, by-passing the site of the ice jam. This can endure for a long time in the case of a soft ice jam where the discharge becomes nearly totally diverted.

"Finally, for locks, it can happen that the discharge remains insufficient to provoke the crushing (or breaking) before the increased heat completely melts the ice in place."

The concept of a "soft" ice jam is further developed by Mathieu and Michel (1967) in another paper.

"The evolution of static ice jams under the effects of pressures sometimes produces the formation of soft ice jams which present in nature situations much more unfavorable than the former....

"Characteristics of the model

"We used a rectilinear concrete canal with a length of 110 feet, having a rectangular cross-section, 6 feet wide. The ice blocks in the ice jam were represented by blocks of polyethelene having the same density as ice ($\rho = 0.92$) and having the dimensions of 1 in. x 1 in. in area with a thickness of 1/4 in. By way of an obstacle to provoke the ice jam, we installed a mobile transverse bar and we made irregularities in the bottom of the canal in the area of the critical section.

"Mechanism of the Feeding

"Refering to the criterion of stability of the static ice jams, defined by the relation (Michel, 1965)

$$\frac{h\sqrt{B}}{\mu\sqrt{Q}} = 2.36 \qquad (1)$$

the formation of the soft ice jam can be arrived at only after the static ice jam has entered a state of disequilibrium provoked by crushing under the effect of the pressures. But, this condition is attained when the term on the left side of the preceding equation is 2.36.

"When the static ice jam enters into disequilibrium, the deformations produced by the crushing of the fragmented cover begins to make itself felt in the zones where the pressures are most intense. These deformations are accompanied by a movement of expansion following the displacement by successive thrusts of the accumulation toward downstream. At the same time the important concentrations of blocks move under the rigid obstacle which detains the ice jam, converging toward the open spaces, that is to say, those where the flow velocity is the greatest.

"If the critical section presents sufficient irregularities to obstruct the passage of the blocks which seek an opening, the capacity of evacuation of the openings is not sufficient to absorb the increasingly dense advance. The roughness of the bottom irregularities combine themselves with those of the lateral surfaces to increase the resistance offered to the blocks and to retard in the first place the solid discharge to the two transverse extremities of the accumulation. We also provoked a complete blockage of the section of flow through solid transport and the immobilization of the mass. We were then in the presence of a soft ice jam.

"Principle characteristics

"The discharge by infiltration and the configuration of the water level are the principle signs that distinguish the soft ice jams from the static ice jams. Once the soft ice jam is formed, the discharge filters through the mass with an appreciable loss of force, and the water level takes on a parabolic shape along the entire length of the flow. The amplitude of this loss of force depends to a degree upon the compaction of the blocks. The smaller the pore volume in the interior of the mass, the greater will be the loss in force. Near the upstream extremity of this parabolic curve the water level retakes (or recovers) its linear slope affected by the diverse thicknesses attained by the fractured cover.

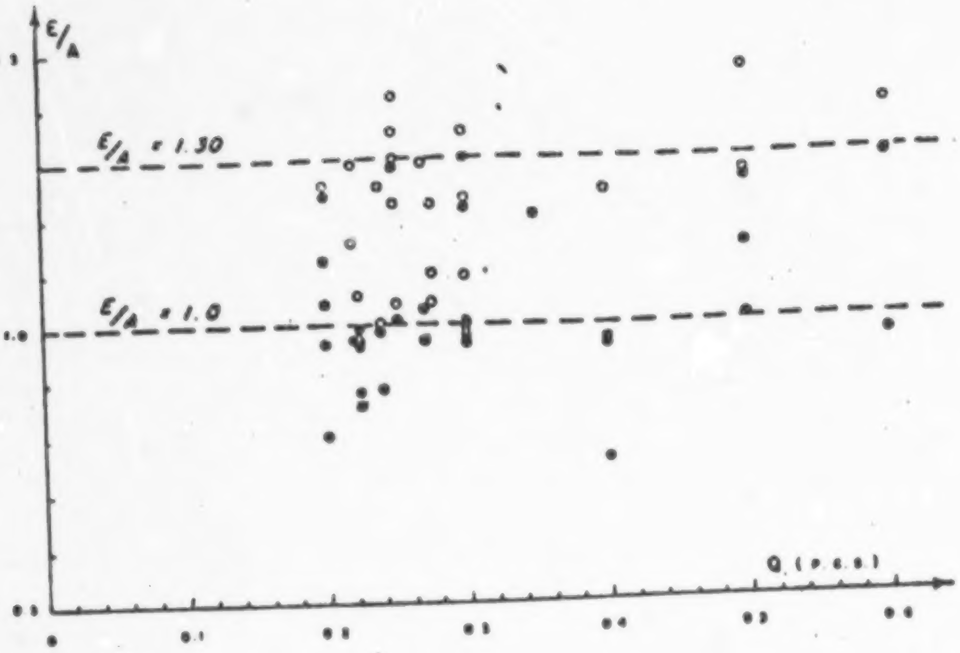
"Analysis of our observations

"Unfortunately the dispersion of the points of data represented on the graph in figure 1, the relation $E/A = 1.0$ shows that for a spacing E under a rigid obstacle $<$ the largest dimension of the block, A, the disequilibrium provokes the trapping of the blocks between the upstream extremity of the lower wall of the rigid obstacle and the bottom irregularities. On the contrary, the relation $E/A = 1.3$ determines the maximum space E with which it is possible to begin the complete blocking of the section of flow.

"For the conditions corresponding to the zone delimited by these relations, the immobilization of the mass is brought about by a temporary juxtaposition of the blocks side by side, then when a part of one rests coincident between the mass and the upstream face of the solid cover and the other part is supported by the irregularities of the bottom. The lack of concord existing between the points situated toward the interior of this zone depends upon the following factors: the irregularities have not been fixed to the revetments of the canal, their position can favor an augmentation or a diminishing of the possibilities of hooking (or fusion) between the blocks; the violence of the pressure which is a function of the volume of the solid mass, the discharge and the height of the water which regulate in some way the intensity of the advancement during the disequilibrium of the ice jam; the pull of the water on the rigid obstacle which slows the sliding of the ice jam and favors the mechanism of the juxtaposition described above. In addition to influencing the start, the incidence of these factors equally affects the persistance of the soft ice jams.

"Conclusion

"It is important to realize that we have only considered a rectangular section in a rectilinear trough. There now remains a pile of conjectures to be scrutinized by bringing in the particulars of irregular and very complex topographies. In nature, each of these factors of the formation of ice jams of this type becomes an individual case because their configuration changes between one and another, and that the conditions of flow vary from one year to another."



Formation of a soft Ice Jam probable, for $E/A < 1.0$
Formation of a soft Ice Jam possible, for $1.0 < E/A < 1.30$
Formation of a soft Ice Jam improbable for $E/A > 1.30$
E = opening under the upstream end of the rigid obstacle (in.).
A = the largest dimension of the blocks = 1.414 in.

Key:
● - formation of soft ice jam
○ - continual disequilibrium of the ice jam

Figure 1. Results of relative experiments of the formation of soft ice jams. (Mathieu, Michel, 1967)

Deslauriers (1965) describes the results of some investigations on the Chaudiere River in Quebec to determine some of the basic physical laws governing ice jams. The Chaudiere was selected because "... it could be typical enough to allow conclusions as general as possible. In spite of its limited importance and of its specific characteristics and difficulties, the Chaudiere reveals itself as quite a good typical model for ice-jam studies and for remedial projects.

"The factors mainly responsible for the pecularities of its regime can be grouped as follows:

1) Natural hydraulic deficiencies, and above all a too long stretch (40 miles) of dead or low velocity waters.

2) South-North bearing... with characterized climatic differences between upper and lower Chaudiere.

3) All day normal coincidence, between solar path and ground slopes.

4) Relative bareness and steepness of the upper basin....

5) Heavy sedimentary discharges... plus... encroachments from individuals and municipalities.

6) Numerous natural and artificial singularities, particularly in the section of Dead waters (sic).

7) In the recent past, there were certain deformations of the hydraulic regime traceable to maintenance and operation of industrial dams....

"The damages attributed to the river are to be distinguished between: (a) icy floods; (b) summer floods.

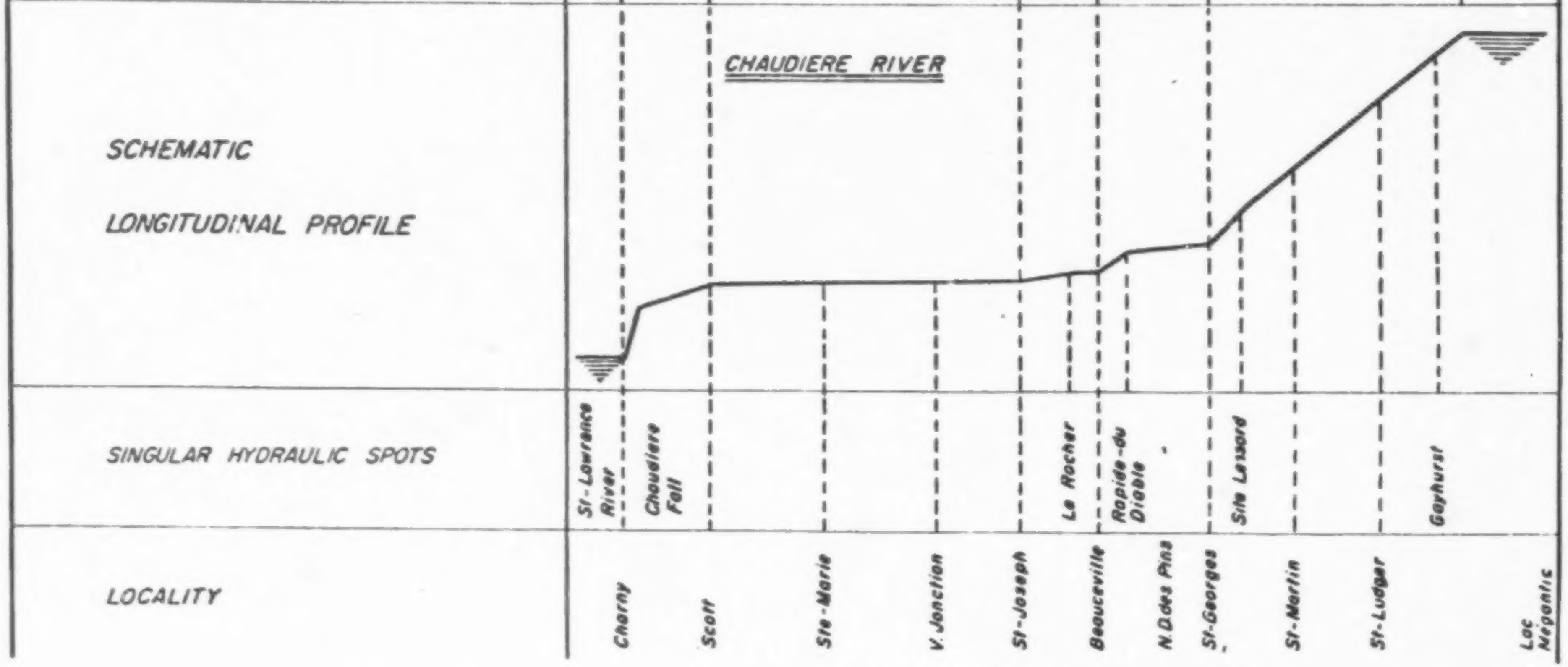
"The areas mostly affected are... in the Middle Chaudiere and in Dead Waters (Fig. 1). The distribution of the damages between these two sections is as follows:

a) Icy floods affect regularly the area of the Middle Chaudiere...

b) Summer floodings are customary over the low lands bordering the 'Dead Waters'....

"It is rather remarkable that a certain similarity is usually granted to..." cover formation and break-up. "As outlined by the following comparisons, they differ essentially both by the involved factors and by the dominating characteristics:

REACH Nº		4 Lower	3 Dead Waters		2 Middle	1 Upper	
LENGTH IN MILES		24	27		13	66	
DIFFERENCE IN LEVEL (FEET)		278	20		81	711	
MEAN SLOPE (FEET PER MILE)		11.6	0.375	138	6.2	14.6	
HYDRAULIC REGIME		rapid	slow (dead waters)		transi-tory	supercritical	
MAIN TROUBLE		nil	Floods			nil	artificial regulari-sation
FREQUENCY AND MEAN VALUE OF DAMAGES		nil	1 in 10 years ($33,250)	1 in 4 years $84,200	1 in 4 years $84,200	nil	


SCHEMATIC
LONGITUDINAL PROFILE
CHAUDIERE RIVER
SINGULAR HYDRAULIC SPOTS
St-Lawrence River
Chaudiere Fall
Le Rocher
Rapide-du Diable
Ste Lassard
Gayhurst
LOCALITY
Charny
Scott
Ste-Marie
V. Jonction
St-Joseph
Beauceville
N.Ddes Pins
St-Georges
St-Martin
St-Ludger
Lac Megantic

Summer Floods Icy Floods

Figure 1. (Deslauriers, 1965)

Item	Cover formation	Cover break-up
1) Determining factor	Temperature of water in the stream	Runoff awakening on the watershed
2) Primary phenomenon	Formation of crystal flakes in the prevailing flow	Formation of undercover uplifting forces by the increasing flow
3) Early development	Progressive agglomeration of crystal flakes in floes of regular forms and limited dimensions	Disengagement of the ice cover from the shore, appearance of cracks and of local submergences
4) Normal progress	Upstream	Downstream
5) General character	Gradual and easy	Abrupt, rapid and steeplechasing
6) Hydraulic transport	Ascending suspension for the crystal flakes and progressive accumulation of incoming floes at water surface	Outbreaks from floating ice fields, undercover runs by lone blocks, the whole in a series of jams and releases
7) Primary consequences	Increase of prevailing depth of flow in the newly covered sections	Decrease of prevailing depth of flow in the newly freed sections
8) Ultimate consequences on the discharge	None in general	Major or persistent jam storages followed by abrupt or lean releases
9) Menance to riparian lands and structures	Local inondations (sic) generally of limited extent and duration	Destructive icy floods and waves whose violence, extent and duration are almost unpredictable."

"The above distinction with reference to the time of occurence leads to a more indicative classification: prematured, matured and over-matured breakups.

Class of break-up

Item	Prematured	Mature	Over-matured
State of destruction			
a) thickness reduction	none	negligeable	apparent
b) ice quality and strength	original	nearly original	greatly reduced

c) adherence to shore	firm	inconsistent	inexistent
d) cover continuity	total	fairly destructed	generally disappeared
Accumulated influences			
a) solar radiation surface	none	negligeable	apparent
b) underneath melt by flowing waters	none	generally negligeable	consequent
c) hydromechanical disengagements, cracks and submerges	none	fair	overcomed by thermal influences

"It is certainly true that such a tabular form of presentation is lacking many serious considerations and incidences....

"The main points to note are that:

1) winter break-ups are essentially prematured and, consequently represent major possibilities for difficulties and damages.

2) springtime or over-matured break-ups are usually calm and of little consequences.

3) all break-ups include two distinct phases: the pre-break-up and the break-up itself.

4) for Chaudiere River, as for any other similar stream, disappearance of ice is usually the result of an hydraulic transport-rather than a melting process.

"Process and mechanism of the break-up

"Excepting contrary influences exercised by the latitude or by other causes, break-up progresses downward.... Nevertheless, the liberation is not a successive process from source to mouth. It is more generally some type of simultaneous destructions at rapids and at points of major inflow. As a matter of fact, the break-ups of the tributaries are earlier than those on the main. Often, when the general liberating wave occurs on the main, large sections of it are encumbered by the ice debris from the tributaries or liberated by local early break-ups.

"Types and characteristics of ice-jams

"... On the typical river, three important types of ice-jams are likely to occur:

a) the lock ice-jam;
b) the stranted ice-jam;
c) the exhausted flow ice-jam.

"... Identification of the type of ice-jam likely to occur at a specific spot can lead to certain objective conclusions with regard to probable duration, height of blockage and importance of resulting damages.

"The characteristics of ice-jams depend on the degree of maturity of the break-up, on the hydraulic singularities of a channel spot and on the ice volume that can be packed there at a certain moment. Information acquired from local experience and derived from a thorough study of the channel are the instruments permitting a certain forecast as to the type of ice-jam likely to occur within a given section of the river.

"Hydraulic elements of break-ups

"A flood wave starts the whole break-up process. Ice debris accumulate at singularities and block the passage of water (fig. 3.1). According to its amplitude and speed, the flood produces serious reactions: it either rolls up the ice cover (fig. 3.2) or pushes it downstream (fig. 3.3). Three points are to be remembered:

1) Passage of a long period wave (fig. 3.5),... is the hydromechanic cause of the cover's liberation.

2) Exhaustion of the wave or its gradual breaking... is the measure of the degree of difficulty for break-ups.

3) Lock action by which the flow reconstitutes its live force: it is the ice-jam.

"Hydrodynamic elements

"a) The daily flood-wave... happens late in the afternoon, lasts only a few hours (fig. 3.4) and the base of its hydrogram seems to keep relatively independent of the flood volume; consequently there is a gradual increase in steepness of the curve as springtime goes by and, soon, snow melt produces a destructive wave.

b) Liberting or transition wave.

The principal characteristics of that wave are (fig. 3.5):

Celerity of its front	$c=gh_0$
Discharge:	$Q=zbc$
Volume:	$V=zbL=2\ bct$
Energy:	$E=1/2\ Mc^2$

where: b = width of the channel
t = time
g = gravity force
M = mass

c) Hydraulic singularities of the channel.

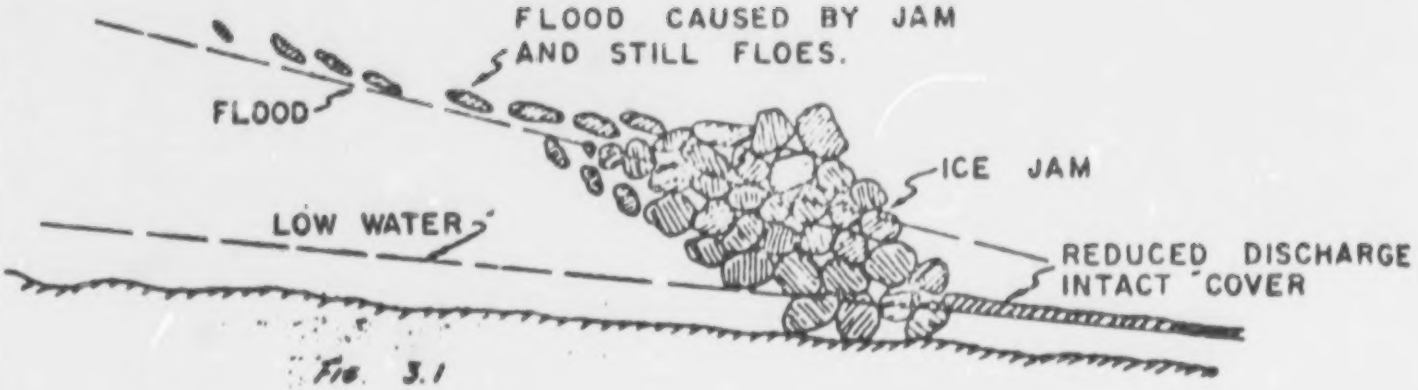

FLOOD CAUSED BY JAM AND STILL FLOES.
FLOOD
ICE JAM
LOW WATER
REDUCED DISCHARGE
INTACT COVER

Fig. 3.1

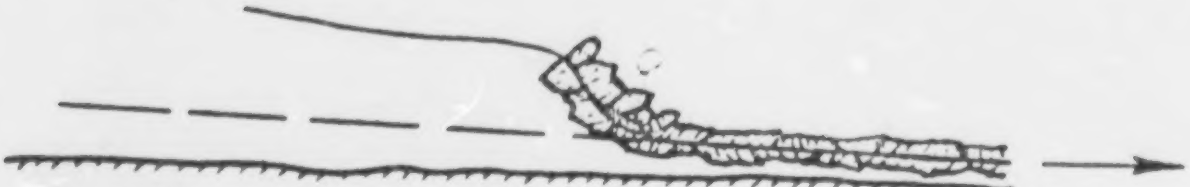


Fig 3.2

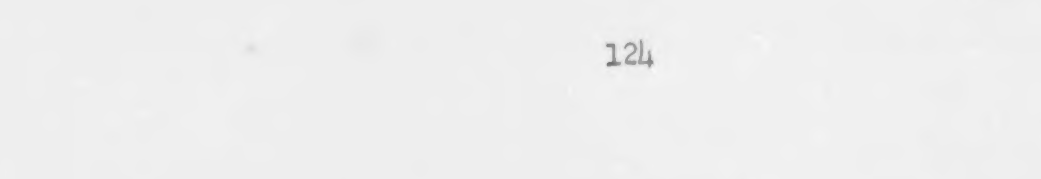


Fig. 3.3

(Deslauriers, 1965)

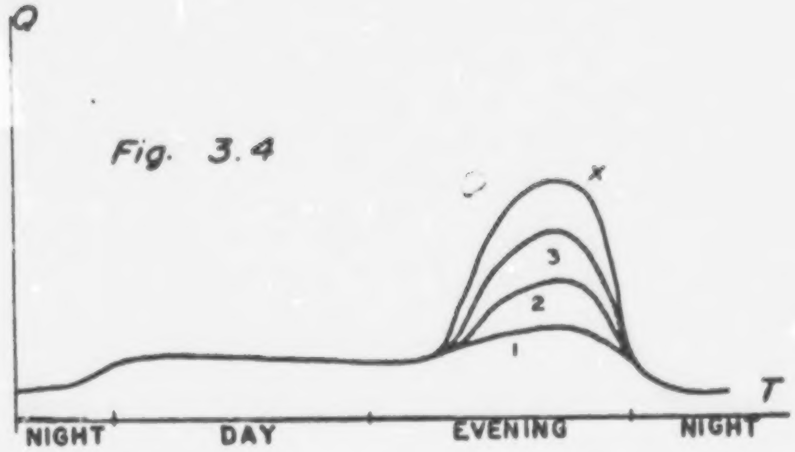


Fig. 3.4

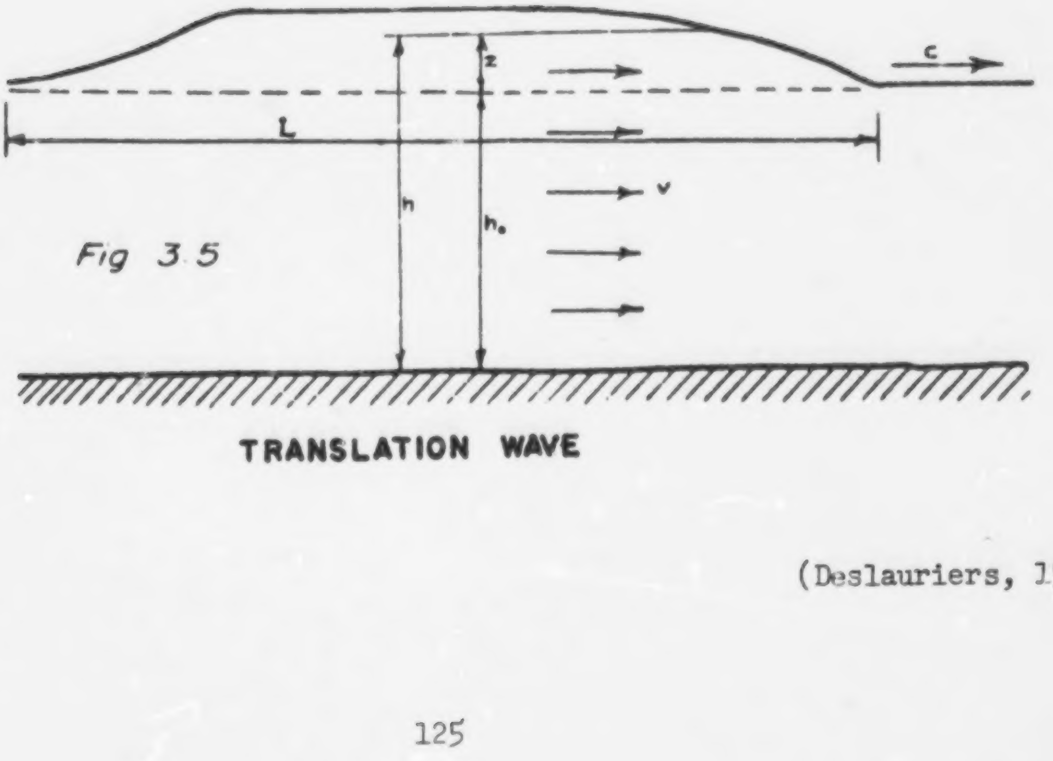


Fig 3.5

TRANSLATION WAVE

(Deslauriers, 1965)

"The task is to find out which singularities provoke ice-jams.... They must also be mathematically studied in relation with a bed topometry thoroughly measured and under the light of a detailed hydraulic analysis for the flow regime.... "

"Chezy-Manning's formula, for open-channel flow, gives the relation between the various hydraulic characteristics of sections; at sections mostly affected by ice-jams, we can determine hydraulic influences upon the phenomena. DuBoys-Brown's formula, for alluvial channels, reveals the section stability and its relation with jamming conditions. Pavlovskii's equations are useful for analysing flow conditions during the winter, and the raising of the depth of flow caused by the ice cover. Schoklisch's equation is merely indicative of the surface's capacity for jamming. Those theoretical notions are used exclusively to realize remedial works by regularization of the bed. Other analyses, not mentioned here, cover the mechanism of break-up itself.

"The use of such relation is chiefly indicative: numerical values are not important by themselves, it is rather variations of the values with the channel's characteristics that count."

Nezhikovskii (1963) describes some methods of calculating slush and ice flow on rivers and proposes a new method.

"The article presented here contains the results of an investigation on the problem of calculating and forecasting the flow rates of slush and ice in plains rivers and rivers partially in the mountains, chiefly with respect to the purposes and tasks of studying ice-jam phenomena....

"Without data concerning the quantity of ice material that is floating down at the upper boundary of the jam, or the edge of the ice, it is impossible to calculate or forecast the accumulation of the ice material in the river bed, its movement, etc....

"Aside from the quantity of ice material, it is also important to know its physico-mechanical properties. If friable slush floats up to the edge, which slush, because of its low buoyance and lack of strength, is easily carried away by the current under the ice cover, the edge will remain almost in one place, and the jam will intensify. If large, strong ice floes approach the edge, it will move rapidly upstream and the rise in the level due to the ice jam will turn out to be insignificant."

"According to the methodology accepted at the present time (Gidrometeoizdat, 1957), the measured flow rate of slush and ice in a range, in a case of uniform cover with respect to the width of the river, is the product of four co-multipliers

$$Q_{ш+л} = B_{м.з} v_{ср.\ пов} \eta a_{ш+л}$$

[$Q_{ш+л}$ = Q_{sh+l}; $B_{м.з}$ = $B_{m.z}$; $v_{ср.пов}$ = $v_{sr.pov}$.] or (1a)

$$Q_{ш+л} = B_{м.з} v_{ср.\ пов} \eta h_{ш+л}, \qquad (1b)$$

where:	$B_{m.z}$	is the width of the river between the shore ice,
	$v_{sr.pov}$	is the mean velocity of the motion of the slush and ice (assumed as equal to the mean surface velocity of the current - see below),
	η	is the cover factor (the area of the river mirror between the shore ice, covered with floating slush and ice, in fractions of a unit),
	a_{sh+l}	is the weight of the ice and slush in 1 square meter of the floating ice formations (average in a cross section),
	h_{sh+l}	is the average thickness of the floating ice formations in the cross section.

With non-uniform cover, in particular when the slush does not float along the entire width of the river, according to the Nastavleniye, the cover factor is calculated in accordance with the expression

$$\eta = \eta_1 b_1 + \eta_2 b_2 + \dots + \eta_n b_n,$$

where:	$b_1, b_2, \dots, b_n$	is the width of the strips into which the river is divided ($\sum b = B_{m.z}$)
	$\eta_1, \eta_2, \dots, \eta_n$	are the cover factors for each strip individually.

According to Gotlib, Zaymin, Smolin, Vasiliskov, Gorisor, Tizdel (1959) with a non-uniform cover, it is recommended that the flow rate of the ice material be determined by the detailed method:

$$Q_{ш+л} = (\eta_1 b_1 v_{пов.\ 1} + \eta_2 b_2 v_{пов.\ 2} + \dots + \eta_n b_n v_{пов.\ n}) a_{ш+л}.$$

[$v_{пов}$ = v_{pov}.] where $v_{pov.1}$, $v_{pov.2}$, ..., $v_{pov.n}$ are the mean surface velocity for each strip individually....

"The width of the river between the shore ice ($B_{m.z}$) or the width of individual strips (b_1, b_2, ..., b_n) is determined by means of a theodolite.... The cover factor η is equal to the ratio of the sum of the time of the passage of the ice floes through the intersection of the cross-hairs of the theodolite to the entire time of observation.... The surface velocity of the current v_{pov} is measured by floating ice floes. Finally, to determine the weight of the ice material ($a_{sh+\underline{1}}$), a special instrument is used - a slush-bathometer....

"In accordance with the methodology used in the Hydrometeorological Service (Gidrometeoizdat, 1957), we obtain data concerning the flow of slush and ice in weight units.... The slush in the ice jam, although it is subjected to packing, nevertheless remains friable. Therefore, we also need information concerning the flow of slush in volumetric units.... Note 1: By flow rate in volumetric units of the packed mass we mean the flow rate in the calculation of which for the thickness h_{sh+1} we assume the thickness of the layer of slush in the slush-bathometer after it is withdrawn from the flow, and by flow rate in volumetric units of unpacked mass, we mean the thickness of $h_{sh+\underline{1}}$, measured in the flow."

"With all favorable conditions, even by means of instrumental measurements we cannot provide for a high level of accuracy in determining the flow rate of slush and ice.... The accuracy amounts to 10-12 percent...."

"Calculation of the flow of slush and ice in the absence of observations.

"Width of the river between shore ice

"Let us consider at first the question of calculating the width of the river between the shore ice in straight-line sections of the river, and then the problem concerning the ratio between this width and the width of the river as a whole.

"For each point for the calculation of the flow of slush and ice and for the hydrometric range, which also were precisely located in straight-line sections, we constructed connections of the width of the river between the shore ice and the width of the river with an open river bed, as a function of the flow rate of the water $B_{m.z} = f\ (Q)$ and $B_0 = f\ (Q)$....

"On the basis of curves $B_{m.z} = f\ (Q)$ and $B_0 = f\ (Q)$ for each range we obtained curves of the connection of the width of the river between the shore ice and the width of the river with an open bed $B_{m.z} = f\ (B_0)$ at the same flow rate of the water. In each curve of $B_{m.z} = f\ (B_0)$ we defined three sections: 1) $v_{0,sr} < 0.5$ m/sec; 2) $v_{0.sr} = 0.5\text{-}1.0$ m/sec; and 3) $v_{0,sr} > 1.0$ m/sec.

The average connection lines have the form of straight lines, going from the beginning of the coordinates,

$$B_{м.\,з.} = mB_0. \qquad (4)$$

"The dependence of the coefficient m upon the predominating $v_{0,sr}$ within the range is described by...

$$m = 0{,}42 v_{0,\text{ср}}^{0.20} + A. \qquad (5)$$

Combining (4) and (5)...

$$\text{"}\quad B_{\text{м.з}} = B_0 \left(0{,}42 v_{0,\text{ср}}^{0.20} + A\right). \qquad (6)$$

"Approximate values of A for rivers with different shapes of the riverbed are indicated in Table 2....

"The ratio of $B_{m.z}$... on the whole river to $B_{m.z}$ on a range for calculating the flow of slush and ice... was found to be... 0.90.

"Velocity of motion of slush and ice

"With a cover factor $\eta \leq$ 0.80-0.82, the average velocity of the motion of slush and ice in an observation range... is equal to the average surface velocity of the current between the shore ice. On the whole, for a large section of the river where, of course, there are turns, compressions, etc., in which the degree of cover is increased, the limit indicated must be reduced to $\eta \leq$ 0.75-0.80. With greater cover factors, the velocity of the motion of the slush and ice is somewhat less than the surface velocity of the current....

"A direct generalization of the local connections $v_{sr.pov} = f\,(Q)$ is impossible, since, with one and the same flow rate of the water, the velocity of the current depends upon the depth of the river, its slope, and the roughness of the bed.... At a given flow rate of the water, the average surface velocity of the current between the shore ice, $v_{sr.pov}$, must be greater than the average velocity in the cross section with the open bed $v_{0,sr}$, but less than the maximum surface velocity ($v_{0max.pov}$) $[v_{0\,\text{макс.пов}} = v_{0\,max.pov}]$. This gives...

$$v_{\text{ср. пов}} = f\left(\frac{v_{0,\text{ ср}} + v_{0,\text{ макс. пов}}}{2}\right).$$

TABLE 2

Values of Parameter A in Formulas (5) and (6)

① Характеристика русла	② $v_{0,\text{ ср}}$, м/сек.			
	0,4—0,7	0,8—1,0	1,1—1,3	1,4—1,7
③ Берега крутые и обрывистые, мелководная зона отсутствует	0,54	0,53	0,52	0,51
④ Берега пологие, мелководная зона имеется	0,45	0,46	0,47	0,48

1) Characteristics of the riverbed; 2) $v_{0,sr}$, m/sec; 3) Steep and bluff banks, shallow-water zone absent; 4) Sloping banks, shallow-water zone present. (Nezhikovskii, 1963)

"The connections indicated were constructed for 18 points. The equation of the center line... has the form

$$v_{\text{ср. пов}} = 0{,}93\left(\frac{v_{0,\text{ ср}} + v_{0,\text{ макс. пов}}}{2}\right). \quad (7)$$

"In the use of formula (7), there may be cases when we will have only one of the quantities needed for the calculation. In this case ...

$$v_{\text{ср. пов}} = 0{,}77 v_{0,\text{ макс. пов}}, \quad (8a)$$

$$v_{\text{ср. пов}} = 1{,}06 v_{0,\text{ ср}}. \quad (8b)$$

"Ice-moving capacity of the river bed

"The product of the first two co-multipliers... ($B_{m.z}v_{sr.pov}$)... characterizes the ice-moving capacity of the river bed....

"For the period of existence of drift shore ice, each of the two co-multipliers... depends upon the flow rate of the water in the river. Therefore, it is pertinent to establish a function of the form $B_{m.z}v_{sr.pov}$ f (Q).... Thus, the low limits of the curve $B_{m.z}v_{sr.pov}$ = f (Q) is always determined, namely when Q = 0 and $B_{m.z}v_{sr.pov}$ = 0, and the curve itself $B_{m.z}v_{sr.pov}$ = f (Q), being the product of the two other curves, is always smooth.

"... For the purpose of generalizing them, (the curves) we will bear in mind that as the flow rate of the water decreases, both the width of the river with an open river bed and the width between the shore ice (B_0 and $B_{m.z}$) will decrease, and especially also will decrease the average velocity in the cross section, and the average surface velocity between the shore ice ($v_{0,sr}$ and $v_{sr.pov}$). From this it follows that a connection of the following form must exist:

$$B_{\text{м. з}} v_{\text{ср. пов}} = f(B_0, v_{0,\text{ ср}}).$$

"... A better characteristic may serve as the half-sum of the average velocity in the cross section and the maximum surface velocity,

$(v_{0,sr} + v_{0,max.pov})/2$.... With respect to the 22 ranges, where data were available these connections were constructed

$$B_{\text{м. з}} v_{\text{ср. пов}} = f\left(B_0 \frac{v_{0,\text{ср}} + v_{0,\text{макс. пов}}}{2}\right)$$

(with the same flow rate of the water in the period of the open river bed and in the period of the presence of shore ice) (Fig. 3)....

"An analysis shows that the local curves for rivers flowing in regions with severe climatic conditions are arranged primarily in the lower half of the graph in" Fig. 3....

"Heat losses from the water surface

"The process of ice formation occurs as a result of losses of heat from the water surface....

a) Radiation component of the heat loss. To calculate the radiation component of the heat balance, we use P. P. Kuz'min's (1961) formula:

$$\begin{aligned} S_n = {} & (Q' + q)_0 (1 - r)(1 - 0{,}14N_0 - 0{,}53N_{\text{н}}) - \\ & - 14{,}4\sigma\varepsilon T_{\text{в}}^4 + 14{,}4\left(0{,}62 + 0{,}05\sqrt{e_a}\right)(1 + 0{,}12N_0 + 0{,}12N_{\text{н}}) \times \\ & \times \sigma\varepsilon T_a^4 \ \text{T cal/m}^2 \text{ per day}, \end{aligned} \tag{10}$$

where:

$(Q' + q)_0$	is the possible daily sum of direct and scattered radiation under conditions of a cloudless sky, in T cal/m^2 per day, (see Bolsenga, 1964),
$\underline{r}$	is the albedo of the water surface (reflection factor),
N_0 and N_{1o} (sic)	are the total and lower cloud cover, in fractions of a unit,
σ	is the Stefan-Boltzmann constant,
$\varepsilon = 0.96$	is the relative long-wave radiation absorbing capacity of water,
$T_v = 273 + t_v$	is the absolute temperature of the surface of the water,
$T_a = 273 + t_a$	is the absolute air temperature,
e_a	is the absolute humidity of the air, in millibars, at a height of 2 m above the water surface."

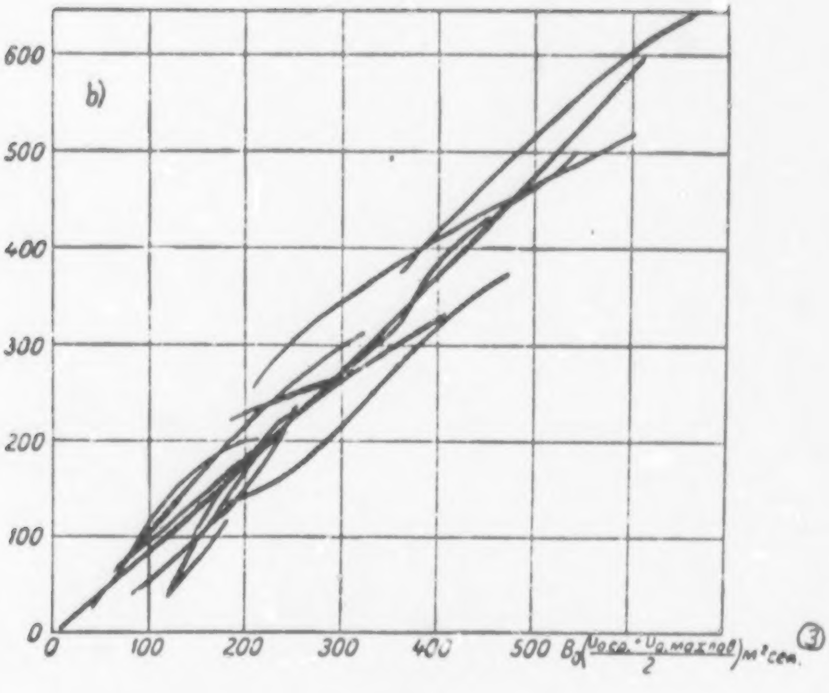


Fig. 3. Combined graph of local dependences. b) $B_{m.z}v_{sr.pov} = f(B_0[\bar{v}_{0,sr} + v_{0,max.pov}]/2)$.

3) $B_0([\bar{v}_{0,sr} + v_{0,max.pov}]/2)$, square meters per second.

(Nezhikovskii, 1963)

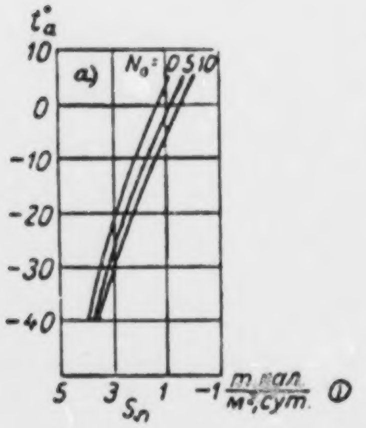


Fig. 4. Nomogram for calculating the radiation component of heat losses (for a latitude φ = 58-62°) for the day. At the isolines the total cloud cover, in balls (i.e., according to a scale with 10 degrees) is written. ① denotes S_n, T cal/m², per day.

(Nezhikovskii, 1963)

b) Heat losses because of convection and evaporation. To calculate heat losses caused by convection and evaporation, we will use the formula of V. A. Rymsha and R. V. Donchenko (1959)

$$S_t + S_e = [(t_{\text{в}} - t_{\text{а}}) + 1{,}56\,[(E_{\text{в}} - e_{\text{а}})]\,(k + 0{,}039\,w_{200})\ T\,\text{cal/m}^2\ \text{per day}\,, \quad (11)$$

where:	E_v (sic)	is the maximum vapor pressure, in millibars, at the surface temperature of water,
	w_{200}	is the wind velocity at a height of 2 m above the water surface, in m/sec,
	k	is a coefficient depending upon the temperature difference between the air and the water....

c) Heat input because of forces of friction, entry of heat from the ground, and arrival of heat carried with ground waters.

"The heat input from the bottom of the river bed in December for a latitude of 58-68°, with a river depth of 4-5 m, according to A. P. Braslavskiy and Z. A. Vikulina (1954), amounts to approximately 0.15 T cal/m^2 per day.

"Heat input to a river bed with ground waters at the end of the summer-autumn low-water period, according to... Chizov (1962), is tentatively estimated as 0.30 T cal/m^2 per day....

"In summary, the magnitude of heat input because of the forces of friction S_v, entry of heat from the ground, and heat input with ground waters, or the magnitude of river-bed heat transfer, amounts to

$$S_v + S_m = 0{,}10 + (0{,}15 + 0{,}30) \approx 0{,}50\ T\,\text{cal/m}^2\ \text{per day}$$

"Thus, the calculation of heat losses by means of the simplified method described above reduces to the use of two nomograms. One of them serves to determine the radiation component and is presented in the form of a function of air temperature and cloud cover $S_n = f(t_a, N_0)$, while the other is used to determine heat losses by convection and during evaporation, and is given in the form of a function of the air temperature and the wind velocity $S_t + S_e = f(t_a, w)$. From the sum of the two items is subtracted the magnitude of river-bed heat transfer (heat input) $S_v + S_m = 0.50T$ cal/m^2 per day.

"... The error rarely goes beyond limits of 5-7 percent.

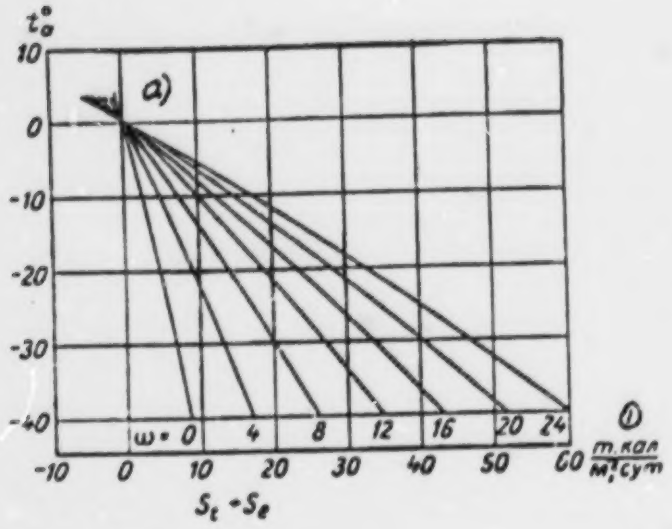


Fig. 5. Nomograms for calculation of heat losses as a consequence of convection and evaporation. At the isolines is written the wind velocity, in m/sec. 1) $S_t + S_e$, T cal/m^2, per day.

(Nezhikovskii, 1963)

"As we have noted, we must consider the fact that during forecasts, as a rule, only data concerning the air temperature may be known. In this case, to preserve the applicability of the very method of calculation, we may make use of local connections between calculated daily heat losses (without river-bed heat transfer) and average daily air temperatures $S = f(t_a)$."

"Analysis of existing proposals for calculation of the flow of ice and slush

"The estimate of the magnitude of the specific flow rate of ice material which is moving in the surface layer... was performed in accordance with data concerning the heat losses S and the length of the ice-forming section L

$$q_{\text{ш}+\text{л}} = \frac{SL}{86\,400 \cdot 80} \, T/sec, \tag{13}$$

where L is in meters and S is in T cal/m^2 per day. In this case a gross error was committed, since it was not considered that with the appearance of ice on the river the ice-forming surface is reduced....

"In 1955-1956 almost simultaneously appeared two works devoted to the calculation of the flow rates of slush and ice with a consideration of the variation in the degree of cover throughout the length of the river, namely works by L. I. Filippova and V. A. Rymsha, (1956)....

"Working from the fact that heat losses occur only from the open part of the water surface, and that the slush being formed is consolidated into lumps with the same weight in a unit of area occupied by it, a_{sh}, T/m^2, Rymsha obtained a formula for calculating the cover factor η in a range separated by τ hours of the trace of the run from the profile of the beginning of ice formation

$$\eta_{\tau\ \text{час}} = 1 - \left(1 - \frac{S}{24 \cdot 80 a_{\text{ш}}}\right)^{\tau}. \tag{14}$$

[$\eta_{\tau\ \text{час}} = \eta_{\tau\ \text{hour}}$; $a_{\text{ш}} = a_{sh}$.]

"If the area that is free of ice at the end of a day's track is accepted for the initial area and if we designate heat losses for the first and second days as S_1 and S_2, and the weights of the slush in a unit of area occupied by it as $a_{sh,1}$ and $a_{sh,2}$, respectively, the expression for the cover factor in a range separated, for example, by 2 days of the track of the run, will have the form

$$\eta_{\text{т},2} = 1 - \left(1 - \frac{S_1}{24\cdot 80a_{\text{ш},1}}\right)^{24}\left(1 - \frac{S_2}{24\cdot 80a_{\text{ш},2}}\right)^{24}. \qquad (15)$$

"The flow rate of the slush on the range (without a consideration of the formation of the ice crust) is obtained, according to Rymsha, as a product of three co-multipliers

$$q_{\text{ш},2} = \eta_{\text{т},2} v_{\text{ср. пов}} a_{\text{ш},2}. \qquad (16)$$

"In order to consider the formation of the ice crust, a correction factor is introduced, depending upon the thickness of the ice crust h_1, calculated in accordance with the formula

$$h_{\text{л}} = \frac{\Sigma S}{80(\gamma_{\text{л}} - \gamma_{\text{ш}})}, \qquad (17)$$

[$h_{\text{л}}$ = h_1.] where γ_1 and γ_{sh} are the volumetric weight of the slush ice and the unfrozen slush. (γ_1 = 0.85 T/m^3), ΣS are the total losses from the surface of the slush ice during the running time."

"The method of L. I. Filippova and V. A. Rymsha in this form, in which it was proposed, has not found any application in practice. Nevertheless, the idea expounded in this method concerning the decrease in the area of the surface that is free of ice as it moves from the beginning of the ice-forming section toward the closing range has found a transformation. In planning practice, during the estimation of the specific flow rate of slush and ice, upon condition of the availability of observations of the degree of cover in the range, the following formula is sometimes used:

$$q_{\text{ш}+\text{л}} = 0{,}5(1-\eta)\frac{\bar{S}L}{86\,400\cdot 80}\ \text{T/sec}, \qquad (18)$$

where L is the length of the ice-forming section, in meters, $\bar{S}$ represents the average heat losses during the run, in T cal/m^2 per day, η is the cover factor in the range....

"Working from conditions of a constancy of a_{sh} throughout the length of the river, A. N. Chizhov (1962), proceeding by a somewhat different route, obtained for calculation of the cover factor this same formula as derived by Filippova and Rymsha. Considering that a_{sh} is unknown, Chizhov proposes to use the connection between a_{sh} and the total heat losses during the time of the run, $a_{sh} = f(\Sigma S)$, constructed in accordance with observation data from two mountain rivers - the Chuand, the Naryn.... The formula is derived from conditions of a constancy of a_{sh} through the length of the river. A connection of the form $a_{sh} = f(\Sigma S)$ testifies to the fact that as the distance from the profile of the beginning of ice formation increases, ΣS gradually increases, and a_{sh} grows accordingly.

"For calculation of the specific flow rate of slush and ice in the absence of observations, N. M. Sokol'nikov (1958, 1954) has proposed the formula

$$q_{ш+л} = (1 - \eta) q_{ш} + \eta q_{л}, \qquad (19)$$

where q_{sh+1} is the flow rate of slush and ice (per unit of width of the river) in T/sec, q_{sh} is the same for slush, $q_{\underline{1}}$ is the same for the ice in the ice crust. The cover factor is determined in accordance with the empirical formula

$$\eta = 3\left(\frac{q_{ш+л}}{2v_{ср.\ пов}}\right)^{1/3}. \qquad (20)$$

"The flow rate of the ice in the ice crust is found in accordance with the formula

$$q_{л} = 0{,}92 h_{л} v_{ср.\ пов}, \qquad (21)$$

where it is recommended that the thickness of the ice crust be calculated in accordance with the formula for the increase in the thickness of the ice proposed by D. N. Bibikov and N. N. Petrunichev (1950), which, at an average wind velocity of 4 m/sec, has the form

$$h_{л} = \sqrt{0{,}04 - 0{,}0013 t_{в}\tau} - 0{,}2. \qquad (22)$$

"The calculations are conducted by means of a gradual selection of the cover factor, since this coefficient itself depends upon the quantity being sought, q_{sh+1}. For this, at first in accordance with equation (13) is calculated–the maximum possible flow rate with an entirely open water surface in the entire ice-forming section and, substituting into formula (20) the cover factor η is determined in the first approximation, and later in accordance with formula (19), the flow rate of the slush and ice, also in the first approximation....

"Trial calculations have shown the limited possibility of applying Sokol'nikov's method for natural rivers....

"A proposed method for calculating the flow rate of slush and ice in volumetric units (in a packed mass)

"With a known width of the river between shore ice and if the average surface velocity is known (see above) the problem of determining the flow rate of the slush and ice reduces to the calculation of the cover factor η and the thickness of the floating ice formations h_{sh+1}....

"Before we commence deriving a calculation formula, we must explain how the thickness and density of the floating ice formations depend upon the degree of cover. For the purpose of solving the problem set for all points for calculating the flow of slush and ice, we constructed connections $h_{sh+1} = f(\eta)$....

"Connections $h_{sh+1} = f(\eta)$, for the greater part, have the form of a parabola, with a very small curvature. Because of the weak dependence between h_{sh+1} and η, the connections $h_{sh+\underline{1}} = f(\eta)$ were drawn in the form of straight lines

$$h_{ш+л} = h_{ш.нач} + b\eta. \qquad (23)$$

"The presence of a free term $h_{sh.nach}$. $[h_{ш.нач} = h_{sh.nach}]$ in expression (23) reflects the fact that at the moment of the origin of lumps of slush, when $\eta \approx 0$, the thickness of them is of a finite magnitude.

"... It was ascertained that the connections $h_{sh+1} = f(\eta)$ are not the same only when the running time in the section $\tau <$ 10-12 hours. With a running time of from 10-12 hours to 4-5 days, the connection $h_{sh+\underline{1}} = f(\eta)$ does not depend upon the length of the ice-forming section....

"... We did not succeed in ascertaining the effect of the velocity of the current on the form of the connection $h_{sh+l} = f(\eta)$...."

"The connections $h_{sh+l} = f(\eta)$ obtained for individual points are of a local nature, and we should consider this in their generalization."

"According to observation data on 28 ranges... the connection between h_{sh+l} and η is described by the following equations:

a) for ranges with a short run in the ice-forming section ($\tau <$ 10-12 hours):

$$h_{ш+л} = 0{,}06 + 0{,}26\eta, \qquad (25a)$$

b) for ranges with a long run in the ice-forming section ($\tau >$ 10-12 hours):

$$h_{ш+л} = 0{,}06 + 0{,}45\eta. \qquad (25b)$$

"Let us now consider the problem of the dependence of the density of slush floating downstream in the form of lumps, mats, and wreaths upon the degree of cover.

"For this purpose, in analogy with the previous problems, an attempt was made to construct local connections of the volumetric weight of the slush upon the cover factor $\gamma_{sh} = f(\eta)$ was made.... For the greater part γ_{sh} had to be determined by means of calculations in accordance with equation

$$\gamma_ш = \frac{a_{ш+л} - 0.85h_л}{h_{ш+л} - h_л}. \qquad (26)$$

"Within the limits of accuracy of the initial data, no dependence of the volumetric weight of the slush upon the cover factor is observed. With a short run in the ice-forming section, on the average $\gamma_{sh} = 0.29$ T/m^3, and with a long run $\gamma_{sh} = 0.45$ T/m^3....

"... We will compile an equation of the balance of ice material on a certain elementary section of the river with a length dL. Let the upper and lower ranges be located on a straight-line section of the river....

"From observations it is known that the cover factor increases as we go downstream. The flow rate of ice materials (in volumetric reckoning) on the upper and lower ranges of the elementary section defined with the same width between the shore ice and the same surface velocity of the current on the ranges, respectively, is equal to:

$$Q_{\text{ш}+\text{л},1} = B_{\text{м. з}} v_{\text{ср. пов}} \eta h_{\text{ш}+\text{л},1}, \tag{27a}$$

$$Q_{\text{ш}+\text{л},2} = B_{\text{м. з}} v_{\text{ср. пов}} (\eta + d\eta) h_{\text{ш}+\text{л},2}, \tag{27b}$$

or, if we consider that the dependence of the thickness of the floating ice formations upon the cover factor is expressed by equation (23), then:

$$Q_{\text{ш}+\text{л},1} = B_{\text{м. з}} v_{\text{ср. пов}} \eta (h_{\text{ш. нач}} + b\eta), \tag{28a}$$

$$Q_{\text{ш}+\text{л},2} = B_{\text{м. з}} v_{\text{ср. пов}} (\eta + d\eta) [h_{\text{ш. нач}} + b(\eta + d\eta)]. \tag{28b}$$

"... Equation (28b) we will transform, ignoring the square of the infinitely small quantity:

$$Q_{\text{ш}+\text{л},1} = B_{\text{м. з}} v_{\text{ср. пов}} \eta (h_{\text{ш. нач}} + b\eta),$$
$$Q_{\text{ш}+\text{л},2} = B_{\text{м. з}} v_{\text{ср. пов}} [\eta (h_{\text{ш. нач}} + b\eta) + b\eta\, d\eta + d\eta (h_{\text{ш. нач}} + b\eta)].$$

"The increment of the flow of slush and ice in the elementary section defined during the time $d\tau$ is equal to the product of the difference in the flow rates on the lower and upper ranges multiplied by the time $d\tau$:

$$B_{\text{м. з}} v_{\text{ср. пов}} d\eta (2b\eta + h_{\text{ш. нач}}) d\tau. \tag{29}$$

"On the other hand, the increment of the volume of flow of slush and ice in the elementary section defined can be determined by means of the product of the area of open water surface of section $\underline{f}$ multiplied by the heat losses during the time of the run $Sd\tau$, with a consideration of the volumetric weight of the slush (γ_{sh}):

$$\frac{fS\,d\tau}{80\gamma_{ш}}. \tag{30}$$

"The total area of the section defined is equal to the product of the average width between shore ice multiplied by the length of the section. We will take into consideration the fact that on the whole for a river the width between shore ice is less than in the straight-line parts of the river bed where observation ranges are usually located. The same thing refers to the elementary section being defined. According to the conclusions obtained earlier, the error of the mirror of the section defined is equal to

$$0{,}9B_{м.з}dL,$$

where $B_{m.z}$ is the width between the shore ice at the boundaries of the section, i.e., the same quantity as in expression (28). The area of the water mirror occupied by floating ice material is equal to

$$B_{м.з}\left[\frac{\eta+(\eta+d\eta)}{2}\right]dL.$$

"The area of open water surface of the section, obviously, is equal to the difference... or, considering the fact that $dL = v_{sr.pov}d\tau$, we will have

$$f = B_{м.з}v_{ср.пов}d\tau\left[0{,}9-\frac{\eta+(\eta+d\eta)}{2}\right]. \tag{31}$$

"Substituting equation (31) into (30), we obtain a different expression for the magnitude of the increment of the flow of slush and ice in the elementary section defined:

$$\frac{B_{\text{м. э}} v_{\text{ср. пов}} S d\tau^2}{80\gamma_{\text{ш}}}\left[0{,}9-\frac{\eta+(\eta+d\eta)}{2}\right]. \qquad (32)$$

"Now equalizing equations (29) and (32), we have

$$d\eta\,(2b\eta+h_{\text{ш. нач}})=\frac{S d\tau}{80\gamma_{\text{ш}}}\left[0{,}9-\frac{\eta+(\eta+d\eta)}{2}\right]. \qquad (33)$$

"If in the right-hand part we open the brackets, we obtain the product of two infinitely small quantities $d\tau d\eta$, which can be ignored. In this case expression (33) is rewritten ... (and by) shifting to finite quantities:

$$2b\int_0^{\eta}\frac{\eta\,d\eta}{0{,}9-\eta}+h_{\text{ш. нач}}\int_0^{\eta}\frac{d\eta}{0{,}9-\eta}=\frac{1}{80\gamma_{\text{ш}}}\int_0^{\tau}S\,d\tau.$$

"The left-hand part is easily integrated. The result of the integration of the right-hand part, i.e., the total heat losses, we will express by means of the product of the average heat losses during the running time ($\bar{S}$ T/cal/m^2 per day) for the running time (τ , days). Then

$$-2b\,[\eta+0{,}9\ln(0{,}9-\eta)]-h_{\text{ш. нач}}\ln(0{,}9-\eta)+c=\frac{\bar{S}\tau}{80\gamma_{\text{ш}}}.$$

"Shifting... to decimal logarithms...

$$-2b\eta-2{,}3(1{,}8b+h_{\text{ш. нач}})\lg(0{,}9-\eta)+C=\frac{\bar{S}\tau}{80\gamma_{\text{ш}}}.$$

"If as the initial reference we accept a range where slush clouds are appearing, then when $\eta = 0$, also $S\tau = 0$. With a consideration of this free term

$$C = -0,1\,(1,8b + h_{ш.\,нач}).$$

"In summary, we obtain a general expression for the change in the cover factor throughout the length of the river because of the total heat losses during the running time:

$$-2b\eta - (1,8b + h_{ш.\,нач})\,[2,3\lg(0,9 - \eta) + 0,1] = \frac{\bar{S}\tau}{80\gamma_{ш}}. \qquad (35)$$

"Generally speaking, we should have substituted the "average" values of parameters γ_{sh}, b, and $h_{sh.nach}$ into equation (35), with a consideration of the individual features of the river and the meteorological conditions that existed at the given moment.... In this case, equation (35) takes the form for the part of the ice-forming section where $\tau <$ 12 hours...

$$-12,1\eta - 28,2\lg(0,9 - \eta) - 1,2 = \bar{S}\tau. \qquad (36)$$

"... When $\tau > 12$ hours, we will work from the idea that volumetric weight of the slush in the flow, on the average, amounts to 0.75 - 0.80 of the volumetric weight in the slush-bathometer, i.e., it is equal to $0.75 \cdot 0.45 = 0.35$ T/m^3.

"With the value of parameters $\gamma_{sh} = 0.35$ T/m^3, $h_{sh.nach} = 0.06$ m, and b = 0.45, in analogy with the previous calculations we obtain, based on the general equation (35), for the part of the ice-forming section after 12 hours of run:

$$-25,2\eta - 56,0\lg[0,9 - \eta] - 2,4 = \bar{S}\tau. \qquad (37)$$

"Equations (36) and (37) are presented in Fig. 8 in the form of nomograms of $\eta = f(\bar{S}, \tau)$.... On the basis of Fig. 8 and equation (25), aside from this a nomogram of $\eta h_{sh=1} = f(\bar{S}, \tau)$ has been constructed (Fig. 9). Such a nomogram is of great convenience for mass calculations, since it makes it possible immediately to determine the product of the second two co-multipliers of the flow rate of slush and ice in a packed mass (in a slush-bathometer).

"A proposed method for calculating the flow rate of slush and ice in weight units

"In order to determine the flow rate of slush and ice in weight units with the availability of a calculated cover factor (and also the width between shore ice and the average surface velocity - see above), we must know the weight of the floating ice material in 1 square meter of the area occupied by it.

"It is known that...

$$a_{\text{ш}+\text{л}} = (h_{\text{ш}+\text{л}} - h_{\text{л}})\gamma_{\text{ш}} + 0,85h_{\text{л}}, \tag{38}$$

where in conformity with the running time, the volumetric weight (density) of slush is equal to 0.29 or 0.45 (in the slush-bathometer). In this equation, only the thickness of the ice crust is unknown to us."

"... The following method of solution appears feasible: to establish from full-scale data the connection of the average thickness of the ice crust because of total heat losses with the open water surface, during the running time $h_1 = f(\Sigma S)$ (namely, as a function of this quantity is determined the cover factor η and the product ηf_{sh+1})....

"For construction of the connection $h_1 = f(\Sigma S)$ (Fig. 10), data from 9 ranges on three rivers were used....

"The connection represented in Fig. 10 may be written...

$$h_{\text{л}} = 0,0074\Sigma S = 0,0074\bar{S}\tau. \tag{39}$$

"Here h_1 is in meters, S in T/cal/m^2 per day, and τ in days.

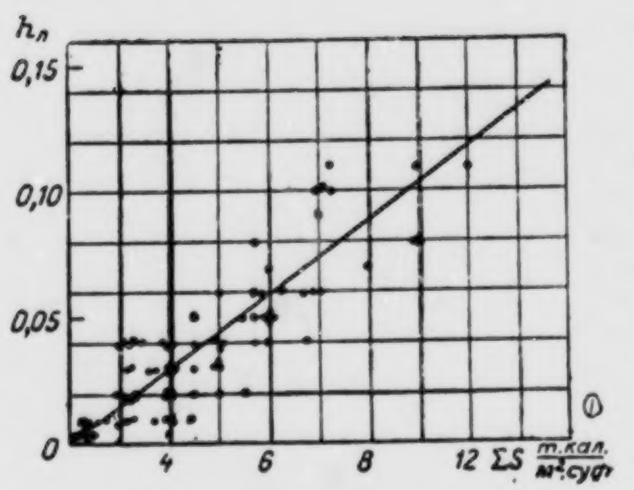


Fig. 10. Average thickness of ice crust h_1 as a function of total heat losses from the open water surface during the running time ΣS. 1) ΣS, T/cal/m^2, per day. (Nezhikovskii, 1963)

"Later substituting formula (39) into (38) and replacing $h_{sh+\underline{1}}$ by η from expression (25), we finally obtain an equation for calculating the weight of the floating ice material in 1 m^2 of the area occupied by it:

up to 0.5 days of run

$$a_{ш+л} = 0{,}02 + 0{,}08\eta + 0{,}004\overline{S}\tau, \qquad (40a)$$

after 0.5 days of run

$$a_{ш+л} = 0{,}03 + 0{,}20\eta + 0{,}003\overline{S}\tau. \qquad (40b)$$

"Calculations in accordance with this equation were performed with the use of the function $\eta = f(\bar{S}, \tau)$ (Fig. 8) and are presented in Fig. 11 in the form of a nomogram of $\eta\, a_{sh+\underline{1}} = f(\bar{S}, \tau)$....

"Using the nomograms presented in Figs. 9 and 11, it is easy to establish, from the observed values of $\eta\, h_{sh+\underline{1}}$ and $\eta\, a_{sh+\underline{1}}$ on one range (range 1), the corresponding values of $\eta\, a_{sh+\overline{\underline{1}}}$ and $\eta\, n_{sh+\overline{\underline{1}}}$ on another range (range 2). This is very important, since the edge of the ice cover is moving all the time and at each given moment of time is located at a different distance from the observation range for the flow of the slush and ice located above it, which preserves a fixed position. For a conversion of the data, it is sufficient to find on the graph the position of the point with respect to the observations on range 1 (such as with respect to $\eta\, h_{sh+1}$ and τ, for example) and, moving upward to τ, the corresponding range 2 (see Fig. 9)."

"Estimate of the accuracy of the proposed method for calculating the flow of slush and ice

"A comparison of the observed and calculated quantities is given in Fig. 13.... The number of errors less than 1/3 of the quantity itself amounts to about 65 percent, which, with a measurement accuracy of 20-25 percent, can be evaluated as a fully satisfactory coincidence...."

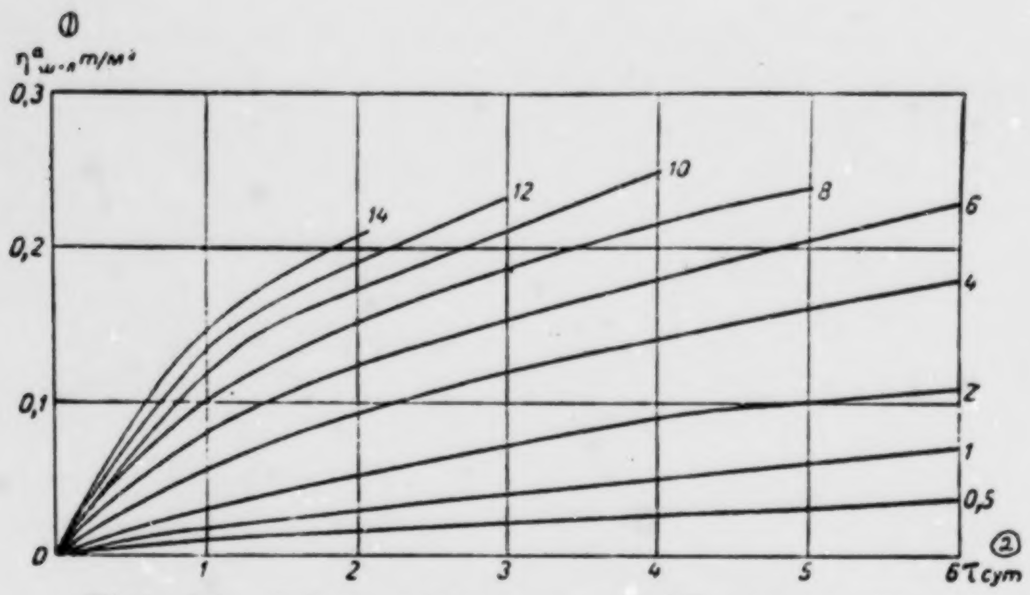


Fig. 11. Graph of $\eta a_{sh+l} = f(\overline{S},\tau)$. At the isolines are written the values of $\overline{S}$ in T/cal/m² per day. 1) ηa_{sh+l}, T/m²; 2) τ, days. (Nezhikovskii, 1963)

$$K = \frac{h_л}{h_{ш+л}}.$$

The corresponding dependence for the determination of K is presented in Fig. 12.

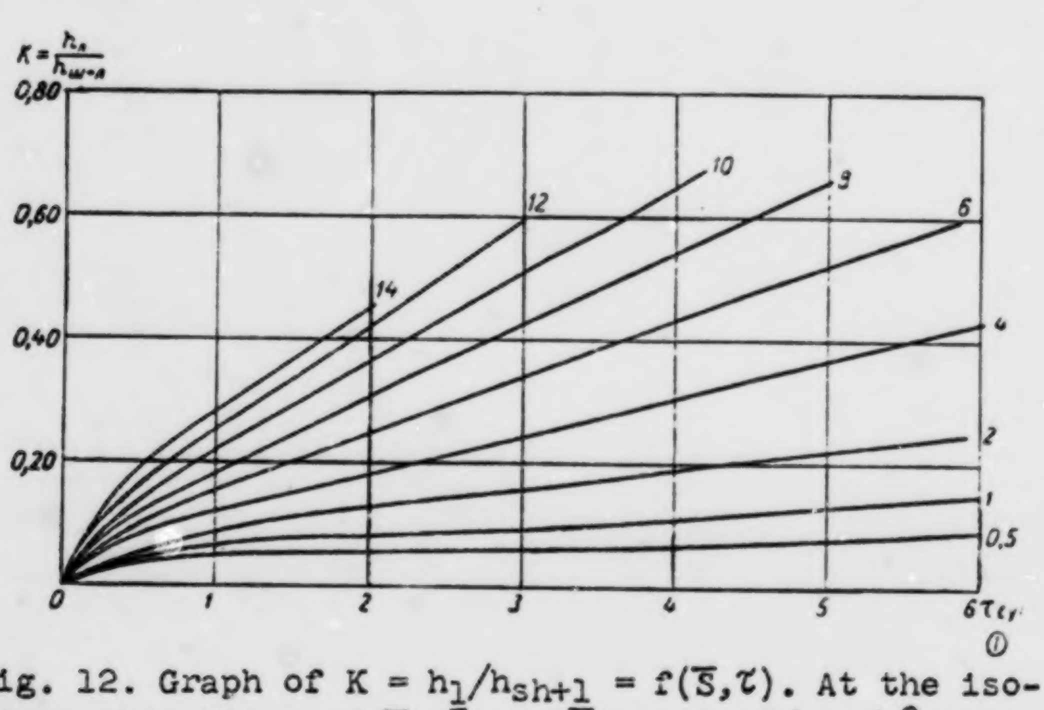


Fig. 12. Graph of $K = h_l/h_{sh+l} = f(\overline{S},\tau)$. At the isolines the values of $\overline{S}$ are written, in T/cal/m² per day. 1) τ, days. (Nezhikovskii, 1963)

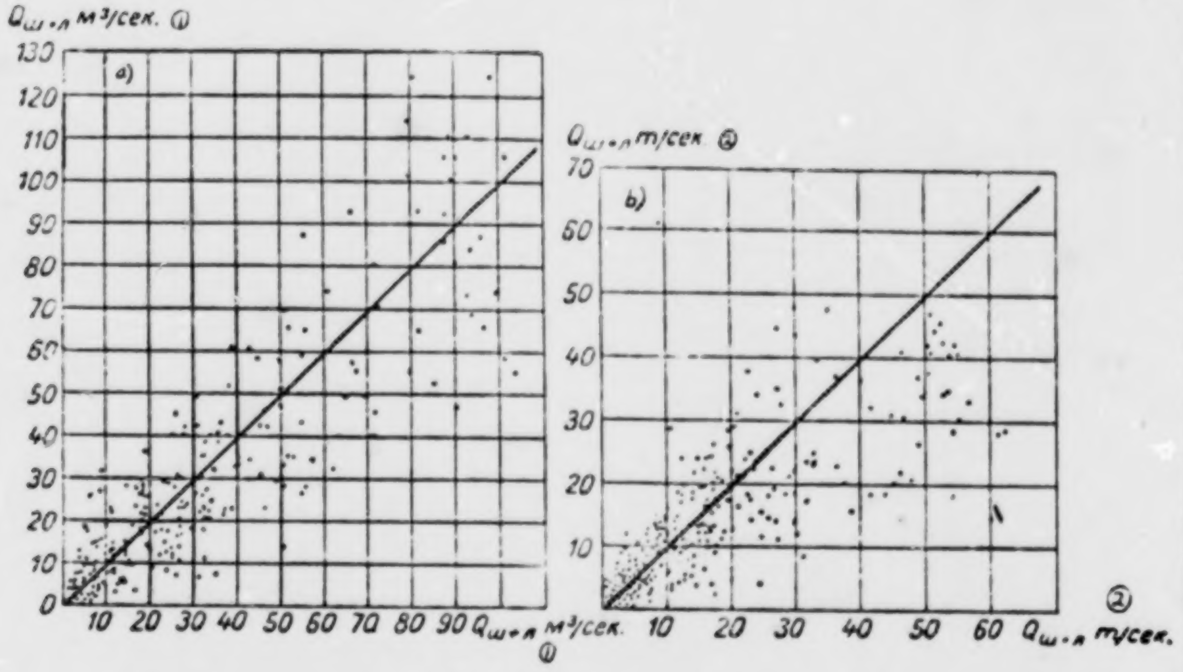


Fig. 13. Comparison of calculated (abscissa axis) and measured (ordinate axis) flow rates of slush and ice. a) In volumetric units of packed mass; b) In weight units. 1) $Q_{sh+\underline{l}}$ m^3/sec; 2) $Q_{sh+\underline{l}}$, T/sec. (Nezhikovskii, 1963)

Piotrovich (1933) develops an equation for the porosity of frazil ice masses under two water level conditions.

"The present work is an attempt at resolving the problems by determinations of the porosity of the frazil accumulations and of the quantity of ice masses in the river jams.

"Let us imagine, for this purpose, a free-floating column of ice in the water with a surface s, volume v, and thickness h (DIAGRAM 1). Assume that the column is composed of crystalline ice having the thickness Δh, density σ, and volume Δv, and of porous frazil ice, saturated with water, having the thickness h_1, density σ_1, and volume v_1.

"Assume the water level to be $h_1 + \Delta h_1$. It is necessary to determine next the porosity of the frazil accumulations.

"... A body floating in the water expels a water mass equal to the mass of the body, in our case, for the density of water equal to the unit, we use:

$$\Delta v\sigma + v_1\sigma_1 = v_1 + \Delta v_1 \qquad (1)$$

"Assuming a unit of volume of frazil with x being that portion of the volume occupied by the ice; σ being the density of ordinary ice; and the remaining portion of the volume being occupied by water, we derive the equation:

$$\Delta v\sigma + xv_1\sigma + (1 - x)v_1 = v_1 + \Delta v_1,$$

or

$$\Delta v\sigma - \Delta v_1 = xv_1(1 - \sigma)$$

therefore

$$x = \frac{\Delta v\sigma - \Delta v_1}{v_1(1 - \sigma)}.$$

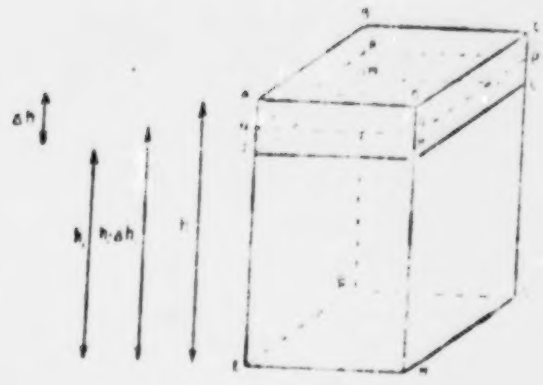


DIAGRAM 1 (Piotrovich, 1933)

ABCDEFGH - ice sheet with thickness $h = AE$
ABCDJKLM - crystalline ice with thickness $\Delta h = AJ$
JKLMEFGH - mixture of water and frazil ice with thickness $h_1 = JE$
ABCD - surface of ice column = S
NOPR - water level

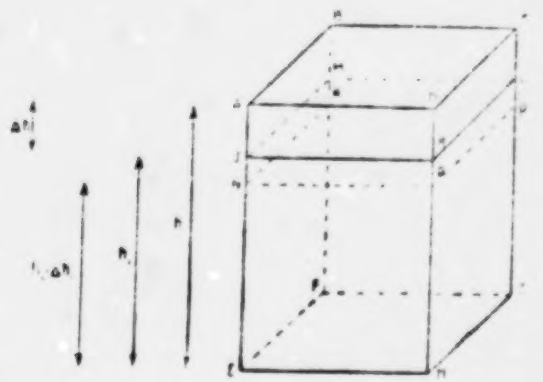


DIAGRAM 2 (Piotrovich, 1933)

ABCDEFGH - ice sheet with thickness $h = AE$
ABCDJKLM - crystalline ice with thickness $\Delta h = AJ$
JKLMNOPR - frazil ice with air spaces $\Delta h_1 = JN$
NOPREFGH - mixture of water + frazil $h_1 - \Delta h_1 = NE$
ABCD - surface of ice column = S
NOPR - water level

We divide by the total surface s, and obtain... the corresponding thicknesses, namely:

$$x = \frac{\Delta h_0 - \Delta h_1}{h_1(1-\sigma)} \qquad (2)$$

It follows that, knowing the water-level and the thicknesses of the designated ice formations, we can obtain an average volume of ice (x) in a unit of volume of frazil. The remaining portion of the unit of volume is occupied, for our purposes, by water, the volume of which will characterize the porosity (p) of the frazil masses, where the average porosity for volume v_1. is written as the difference (1-x):

$$p = (1-x) = \\ = 1 - \frac{\Delta h_0 - \Delta h_1}{h_1(1-\sigma)}. \qquad (3)$$

"Let us examine a second possible situation, namely: assuming the water level to be lower than the crystalline ice; this happens in the case of large pile-up of frazil beneath the ice.

"In this case, in the ice column, there exists a layer (interlayer, space) Δh_1 of porous frazil with the volume Δv_1 (DIAGRAM 2), where the voids between the ice are occupied by air, just as in volume v_1. they were occupied by water.

"Let us state that the porosity of the ice in volume Δv_1 and v_1 is the same (equal); that is, in a unit of volume, the x - portion is occupied by ice, and the (1-x) is occupied either by water or air.

"We then write the equation analogous to (1):

$$\Delta v_0 + \Delta v_1 \sigma_2 + v_1 \sigma_2 = v_1$$

whence:

$$\Delta v_0 + x\Delta v_1 \sigma + x v_1 \sigma + (1-x) v_1 = v_1.$$

Here, we disregarded the weight of air occupying spaces in the frazil ice and in computing x we obtain:

$$x = \frac{\Delta v_2}{v_1 - \sigma(\Delta v_1 + v_1)}$$

or....

$$x = \frac{\Delta h_2}{h_1 - \sigma(\Delta h_1 + h_1)} \qquad (4)$$

and, accordingly, the porosity equals

$$p = (1 - x) = 1 - \frac{\Delta h_2}{h_1 - \sigma(\Delta h_1 + h_1)} \qquad (5)$$

The last equation can be adapted for situations where the frazil accumulations are above the crystalline ice.

"In the presence of a snow cover, an additional member, $\Delta h_3 \delta$, enters equations (3) & (5), where Δh_3 is the thickness of the snow cover, and δ represents its density.

"Actual river conditions encompass a whole series of deviations from the designated ideal situation of a free-floating ice cover, represented in this work by the floating column of ice.

"Such deviations include:

1) the frazil masses, in the observed ice column, were distributed evenly, whereas in actual conditions, frazil is distributed unevenly both along and across the river.

2) the ice cover hinges on and freezes to the shores

3) in the case of ice jams extending all the way down, the ice is supported by the bottom of the river....

"After determining the average amount of ice in a unit of volume on given portions of the ice jam, calculations can be made of the total mass of ice in the jam. This mass is expressed as the sum:

$$M = \sigma \sum_{i=1}^{i=n} s_i (x_i h_i + \Delta h_i)$$

where, σ - is the density of ordinary crystalline ice
s_i - is the surface of a given jam stretch
h_i - is the average amount of ice in a unit of volume x_i.
Δh_i - is the average thickness of the crystalline ice on a given stretch of the river, for the number of stretches in which the preceding elements equal n.

"In calculating the ice masses, we can, without any great degree of error, distribute the average amount of ice x in a unit of volume for a given jam area, unto the nearest stretches which were not included in the computation of the ice volume x.

"Thus, utilizing common measurements from the studies of jams, that is:

1) the thickness of the ice sheet with sub-divisions of frazil and crystalline ice

2) the level of the water from the lower surface of the ice, and measurements of the height and density of the ice cover, we can obtain, with the derived formulas, a representative porosity of the frazil masses, as well as calculations of the quantity of ice masses in jams."

Horvath and Laszloffy (1957) analyze the characteristics of the stoppage of ice on the Danube River.

"Let the magnitude (A, m^2) of the surface of the ice floes passing in unit time through some cross section (1) of the stream be expressed by the hydraulic characteristics of the cross section:

$$A = v_{01} n_1 W_1 \qquad (1)$$

where v_0 is the surface velocity, m/sec;
W is the width of the water surface, m;
n is the degree of ice cover expressing the portion of the water surface covered by ice.
Index (1) denotes the cross section.

"If through cross section (2) downstream in unit time the same amount of ice passes, the degree of ice cover will there be

$$n_2 = \frac{A}{v_{o2} W_2} \qquad (2)$$

or the mean velocity substituted for surface velocity, with consideration of the Chezy formula

$$n_2 = \frac{A}{\alpha . c \sqrt{D_2 S'} . W_2} = C \frac{A}{D_2^{1/2} S^{1/2} W_2} \qquad (3)$$

where D is the mean depth substituting the hydraulic radius, m.
S is the slope of the surface;
c is the coefficient of velocity;
$\alpha = v_o/v$ is the ratio of surface and mean velocity;
and C is the constant.

"According to formula (3) the degree of ice cover increases with the diminution of the slope, of the depth and of the width of the water surface, that is to say, is in close relation with factors describing the state of the channel. Since the slope of rivers generally decreases towards the mouth, n will increase.

"While the ice is drifting, $n < 1$, but the nearer it comes to unity, that is, the denser is the ice drift the more probable it is that the drifting ice floes will accumulate in some bend or on some shoal in the middle and form an ice jam, blocking the way of the other floes that are continually arriving from upstream, and an ice cover will build up, rapidly increasing from the jam upwards.

"The lower the velocity of flow, the more rapidly the thickness of the ice cover grows, for the water particles are in longer contact with the bottom surface of the ice and cool down easier than in faster water, and the mechanical wearing effect of the slow water is also less. The thicker ice cover thus formed is also more resistant, and has therefore a longer life, than the thinner ice cover of the upper reaches.

"All this considered, it may be established that since on gently sloping river reaches the ice stops more easily, gets thicker and has a longer life, in accordance with the general configuration of the longitudinal section of rivers, the frequency of the occurence of ice and the duration of the ice cover has to increase in general towards the mouth of the river. It is, however, evident from formula (3) that this general regularity may be substantially disturbed by conditions of the channel: local changes of slope, depth and width of the water surface, further sharp bends, islets and shoals, which play a decisive part in blocking the ice drift."

"... To present sharply the influence of channel configuration on ice conditions... the ratio of the duration of stationary ice and of the total number of days of ice... which may be called the characteristic of ice stoppage, fully supports the foregoing. The high value of the characteristic of ice stoppage between Dunafoldvar and Drava Mouth (> 60%) clearly shows the want of regulation and gives at the same time the reason for the grave icy floods frequent on this reach. Downstream, channel conditions of the Danube enlarged by discharges of the Drava, Tisza, Sava are so much more favourable as the passage of the ice does not encounter particular difficulties.

"The characteristic of ice stoppage jumps particularly high on the reach downstream from Silistra, where it exceeds 70 and even 80%. On the almost entirely flat maritime section this is all the easier to understand as the Sulina branch is relatively narrow and sluggish, because the major part of the flow is discharged into the sea through the other two branches. Between Braila and Silistra the Danube flows to the north, often stormy north winds slow down very much the velocity of drift of ice floes and facilitate stoppage. The ice cover has been built up here in 90% of the cases independently of the maritime section, that is, stops between Braila and Silistra sooner than before the ice cover of the maritime section could reach Braila."

Angstrom (1937) gives a brief summary of a study on one river in Sweden to develop methods of ice jam prevention.

"The present note will give a short exposition of the theoretical principles on which an investigation of the obstruction by ice in the river Gotaalv has been based. One of the purposes of the statistical investigation was hereby to give possibility of an evaluation of the effect of some artificial arrangements used in order to diminish or prevent the obstruction by ice in the river. As a measure on the ice formation the change in water, caused by the ice, was used. If the normal difference in water level between two points corrected for the velocity of water is h_0 and the observed difference under the influence of ice formation is h_1, the difference $h_1 - h_0 = \Delta$, is taken as a measure on the obstructive effect of the ice.

"The ice formed under given meteorological conditions may now be regarded as a function

1) of a number of meteorological and hydrological factors
2) of some given factors introduced by artificial means.

"In order to investigate the effect of the latter ones, it is of importance to know the natural ice formation in its dependence of the meteorological and hydrological conditions.

"... It is evident from the material at hand that the rate of increase of the ice formation under given meteorological conditions is decreasing with time with a tendency to approach a value Δ_∞ which for the present purpose we may regard as representing stationary conditions. If the meteorological and hydrological factors take the value t, u, v---, at the same occasion when the ice damming is measured, we may consequently put:

$$\Delta_\infty = F\,(t,\ u,\ v - - - - -). \qquad (1)$$

"We further assume the rate of ice formation to be proportional to the difference between Δ_∞ and the actual value of Δ at the moment. We thus have:

$$\frac{d\Delta}{dT} = k\,[\Delta_\infty - \Delta] \qquad (2)$$

"Here k is probably almost independent of the temperature but undoubtly to some degree dependent on the water velocity and chiefly on the wind velocity. What here is of importance to emphasize is the fact, that it seems impossible to assume k to adopt a value of zero. That would namely imply, that we even for great values on $\Delta_\infty - \Delta$, would find no increase in the ice formation, k may be regarded as a measure on the velocity of the ice formation, reduced to a constant value on $\Delta_\infty - \Delta$. In fact the combined influence of the convection and the radiation processes leads to the result that k will keep always a finite value different from zero.

"Under such circumstances we find that under the assumptions just made the only conditions for which $\frac{d\Delta}{dT}$ can take the value zero, is when

$$\Delta = \Delta_\infty$$

"Consequently we arrive at a method to investigate the value of the ice damming at the state of equilibrium in its dependence of the meteorological factors. If we pick out the maximum and minimum values of the ice damming Δ they may be expected to correspond rather closely to the final state of equilibrium demanded by the meteorological and hydrological conditions of temperature, wind, water discharge etc.

"... The most important results are the following:

I) The ice damming Δ_∞ may be expressed as an approximately linear function of the negative temperature, viz.

$$\Delta_\infty = -Ct \qquad (3)$$

where t is the temperature in degrees Celsius....

II) The ice damming shows, under equal conditions in other respects, a rather marked increase with increasing velocity of the water discharge, as soon as the ice damming is above a given minimum value.

"The effect of the velocity of water is hereby a double one, namely as well a natural hydrodynamical one as also a direct influence as regards the accumulation of ice.

"After the statistical investigation was thus carried through for cases, where no artificial precautions had been taken in order to prevent the damming, a similar investigation was made as regards an interval of time, during which ice beams (probably booms) were laid out in order to collect the ice and make the ice damming less.... If, for the case of no artificial factors, we express the ice damming Δ_∞ as a function F (t, u, v, ---) of the meteorological factors, we obtain in the case of prohibitive factors another function:

$$\Delta_\infty = F^{1}\ (t, u, v, ---).$$

"We may now regard the value F (t, u, v,---) F^1 (t, u, v, ---) as a measure on the effectivity of the factors introduced through artificial means. In this way it was possible to arrive at a definite idea about the efficiency of the prohibitive methods used." Figure 2 is included and shows ice damming as a function at the temperature.

Assur and Frankenstein (1963) describe two equations for the "ice jamming number" and the "ice packing number".

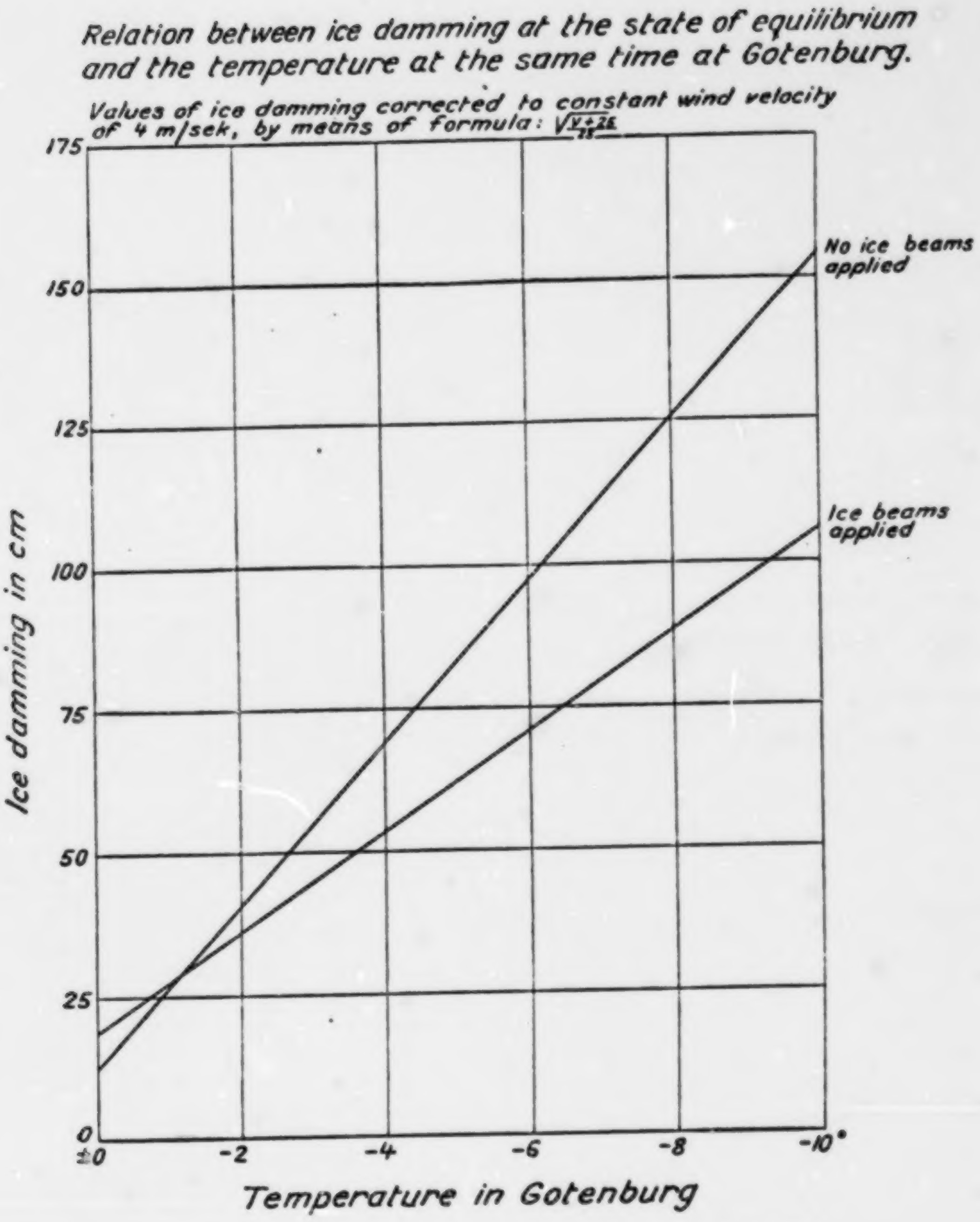


Fig. 2. (Angstrom, 1937)

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Regional Characteristics

Descriptions of the characteristics of ice jams in several regions of the world are given in this section. Some investigators report long term trends. Others describe only individual cases. Either type is useful for comparison to local conditions. More important, if prevention or removal methods used in other regions are considered for local use, the characteristics of the ice jams in those regions should be known. This is due to the fact that techniques depend on the characteristics of jams which occur.

North America

The Niagara River is one of the most extensively studied rivers in North America with respect to ice jams. This is probably due to the frequent occurrence of ice jams which affect power production.

Foulds (1967) describes some ice jam characteristics of the river.

> "Lake Erie and the upper Niagara River produce vast quantities of ice every winter, and virtually all that enters the river, or is made therein, must pass over the falls and downriver to Lake Ontario. There are inevitably some areas which are very shallow, others where downstream currents are inadequate or non-existent, and finally areas where adverse winds tend to restrict ice movements. The problem areas have been identified and operating techniques developed to prevent the formation of an ice cover everywhere except the Maid of the Mist Pool where an ice bridge forms almost every year. The various problems which occur are directly related to the types of ice which come down the river....
>
> "Lake ice
>
> "... Until the winter of 1964-65 it was customary for a considerable quantity of ice from the lake to come down the Niagara River in the early winter until the pieces became large enough to form a natural ice bridge between Buffalo on the United States shore and Fort Erie on the Canadian shore.... Under average wind conditions, this quantity '(volume of ice leaving the lake)' could vary from a few square miles to perhaps 20 square miles in one day.

"Until there was sufficient cold weather to consolidate the ice bridge, and uneasy period existed during which a severe storm could break the arch and force up to 40 square miles of ice per day into the river. Its composition was an amalgam of slush, black ice and white ice, piled together by wind and waves.... The difficulties in passing such material down a river which is less than 10 feet deep in many areas can well be imagined.

"River ice

"There are about 40 square miles of river between Lakes Erie and Ontario ... with the falls located approximately half way between the two lakes.... Between Fort Erie and the upstream end of Grand Island the fall is sufficient to create velocities in excess of 10 feet per second. Water leaves Lake Erie at a temperature very close to freezing, becomes supercooled in the fast flowing rapids and immense quantities of frazil are generated. The velocities in the channels around Grand Island are much slower, of the order of 3 to 4 feet per second, and as a result the frazil comes to the surface, and joins together into huge flocks. This area at the head of the river is also famous for its snow storms being adjacent to a large body of water, and on the downwind side of the principal storm direction, therefore, it should not be surprising to learn that vast quantities of slush ice are also produced. The frazil and slush combines during its seven hour trip downstream to the area where the power intakes divert their water, and the surface layer freezes into a hard pan ... which may be up to two inches in thickness, and may be hundreds of feet in diameter. Under normal circumstances, one to two feet of the softer material adheres to the underside of the pan, but because of shore friction assisted by on-shore winds the pans and soft material may be compressed into layers up to 8 feet or more in thickness."

"Anchor ice

"Conditions are also favourable for the formation of large quantities of anchor ice when the nights are cold and clear, because the entire upstream reach of the river is less than 30 feet in depth and in most cases depths are less than 15 feet....

"River bank ice

"Due to a seiche on Lake Erie, the outflow may increase by as much as 100,000 cfs in as little as four hours, causing a rise in river levels of several feet. This phenomenon creates yet another problem by breaking off huge pieces of ice from the shores of the upper river....

"Lower river

"An ice bridge forms in the Maid of the Mist Pool each year due to a combination of circumstances involving the vast quantities of ice coming from upstream, low velocities, and the narrow width of the gorge. There are large eddies in this pool which further reduce its ability to pass ice downstream....

"No further problems are encountered until the ice passes the high head plants which are located about 8 miles from Lake Ontario. Here the river leaves the gorge and the velocity is substantially reduced. During the 7 hour trip to the lake the effects of wind-chill may combine with low velocity to re-freeze the ice passed down from upstream into large pans. In addition north and east winds over Lake Ontario may prevent the exit of the ice into the lake...."

The Niagara River has an unusual ice jam problem in the reach between the power diversion intakes (above the falls) and the powerhouse near Lewiston, N. Y. (Foulds, 1964).

"For scenic purposes 50,000 cfs, or approximately 30 per cent of the flow in the river in winter must go over the Falls, and the remaining 70 per cent is available for power production.

"The problem simply stated is:- How can 50,000 cfs be made to carry all the ice over the Falls and downriver as far as the powerhouses, (where the diverted flow rejoins the river), when conditions recur which succeeded in jamming the river severely in the past when virtually the entire river flow was available for passing ice."

Strowger (1950) also describes ice jams on the Niagara River. The causes of jams in the upper rapids, Maid of the Mist Pool, and in the lower river are described. The observations are similar to Fould's (1967) report. Some interesting ice thickness measurements during the 1924 ice jam are provided. Ewens (1938) describes early ice jam characteristics in the Niagara River. He recommends certain preventive measures which are now in effect (Foulds 1967, 1964).

Pratley (1938) gives a description of two Niagara River ice jams and details of the destruction of a large bridge. The freezing of Niagara Falls is observed in an early article of the Scottish Geographical Magazine (1936). Conditions prior to water diversion for power are mentioned. Lyon (1912) has described the frazil and anchor ice on the Niagara River.

Ice jam conditions on some connecting channels of the Great Lakes are described by U. S. Board of Engineers of Rivers and Harbors (1921).

"St. Marys River ice effects.-- The retardation of flow in the St. Marys River is due to the ice cover on the river from Lake Superior to the head of the rapids, ice jams in the rapids occuring infrequently if at all....

"St. Clair-Detroit River ice effects.-- ... In addition to the normal ice cover, jams or blockades are of frequent occurences and at times hold back large quantities of water. Blockades usually form in the Detroit River in late December or early January followed in February and March by ice jams in the St. Clair River. These latter continue in April and occasionally into May.... After the breaking of the blockade in the St. Clair River each year there is frequently a blockade of short duration in the Detroit River."

Shipman (1938) tabulated the opening and closing dates of the Mississippi River from 1841 to 1935. He briefly mentions ice gorging conditions during the period studies. "A tabulation of the ice-gorges shows that most gorges of importance occurred before 1890.... It seems that ice-gorges were more frequent in the early part of our record due to colder weather, less river-improvement, and heavier ice-forming in sloughs and pools."

Piers of numerous arch bridges near Lima, Ohio are a factor in ice jam formation on the Ottawa River (Detroit District, Corps of Engineers, 1967).

Hoyt (1913) discusses the effects of ice on stream flow. Problems in collecting accurate records in the presence of ice jams are briefly discussed and some descriptions of field observations of ice jams are given.

Large accumulations of frazil at one section of a river were measured. "... When, however, it is present in sufficient quantities to completely fill the channel it forms temporary jams that raise the water until the ice is overflowed or until the increased pressure pushes the frazil forward....

"Because of the great difficulty in making discharge measurements when frazil is present, few examples are available. The general effect of frazil on cross sectional areas and velocities is, however, shown in the accompanying diagram (fig. 13).

"At the upper section the channel underneath the surface ice was almost completely blocked by frazil or needle ice; at the lower section, 200 feet downstream, there was but little frazil, yet the observed velocities (shown by the figures) at the lower section were so great as to indicate considerable flow through the masses of frazil. The mean of the measured velocities is shown by the contours."

Ice jams on the Red River of the North are described by Hoyt (1913) and Harding (1967).

Stevens (1940) reports an unusual ice jam condition in a shallow stream.

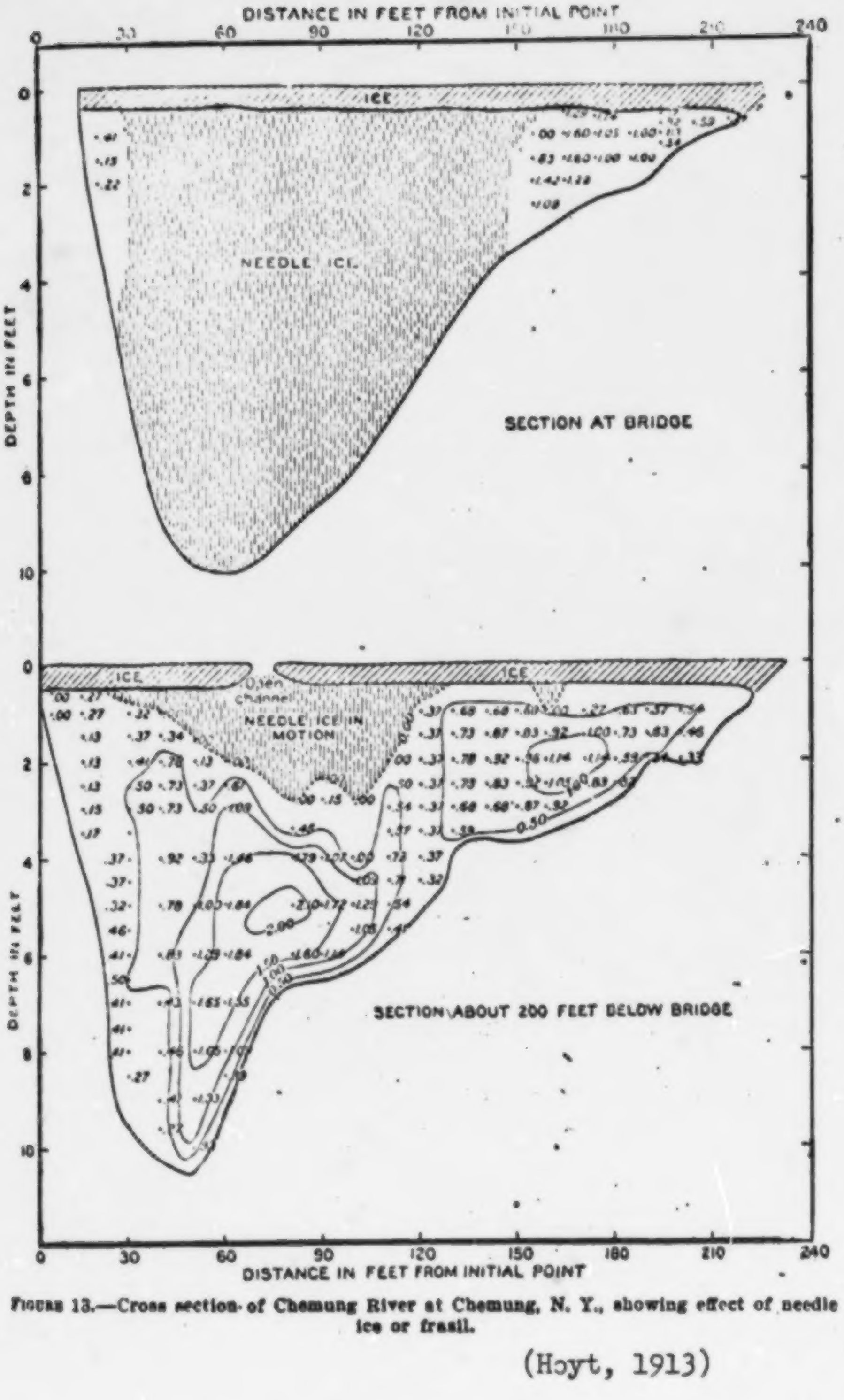
DISTANCE IN FEET FROM INITIAL POINT
0
30
60
90
120
150
180
210
240
DEPTH IN FEET
0
2
4
6
8
10
ICE
NEEDLE ICE
SECTION AT BRIDGE
ICE
Open channel
NEEDLE ICE IN MOTION
ICE
2.00
0.50
SECTION ABOUT 200 FEET BELOW BRIDGE
DEPTH IN FEET
0
2
4
6
8
10
0
30
60
90
120
150
180
210
240
DISTANCE IN FEET FROM INITIAL POINT

FIGURE 13.—Cross section of Chemung River at Chemung, N. Y., showing effect of needle ice or frasil.

(Hoyt, 1913)

"A peculiar phenomenon of ice-gorging may occur during periods of low temperatures in alluvial valleys where the river has comparatively low banks and a fairly steep gradient. When the water becomes cooled below the freezing-point large quantities of frazil ice are produced in the riffles and all other turbulent reaches. In time the flowing water becomes fairly viscous with its suspended load of ice-crystals....

"If the banks are too low to permit the river-stage to rise to the tranquil conditions where surface-ice will form, the banks are overflowed. The river then acts like a stream surcharged with silt. The river flows to the low spots filling them with ice. As it flows slush-ice is deposited wherever velocities are slackened along the edges. In this way the stream builds up a new bed with ice until they in turn are overtopped and the river finds a new channel. This process is repeated many times until, if the cold spell continues, the entire valley-floor may be covered with several feet of ice interlaced with a multitude of braided channels.

"There is another factor that contributes to rapid ice-formation and the diversion of the stream from one place to another. When the river leaves its natural banks and starts flowing across the valley-floor the water may encounter gravel-beds and rocks that have been cooled to the temperature of the atmosphere....

"Madison River, Montana, is a stream that exactly fulfills these conditions...."

Keefer (1898) describes a situation similar to the above report.

"... It is quite conceivable that anchor ice can drive a river out of its bed--cause a winter overflow and the opening of a new channel around a rapid. This possibility may account for some of the 'ancient channels', 'lost channels,' and 'high water channels' to be found in the immediate vicinity of some cataracts, chutes, and rapids."

Garner and Frankenstein (1966) observed ice jam conditions on the White River from its confluence with the Connecticut River to Sharon, Vermont, a distance of 15 miles.

Fletcher in Groat (1918) describes some destructive ice jam action on the Upper Connecticut.

The Rock Island District, Corps of Engineers (1967) classifies three types of ice jams which occur on the larger Alaskan Rivers.

"a. The most common jam is caused by a large floe or ice sheet jamming at a river bend, at a constriction or on a sand bar. The resultant damming of the river by reduction of cross-sectional area causes a backup of the water and junk or slush ice that is moving downstream. Hydrostatic heads as high as 23 feet have been reported because of jams of this type. This type of jam may also occur in a stair-step pattern where one jam causes a slight backup; a second jam a slightly greater backup; and so on upstream, for many miles....

"b. A second type of jam occurs when a solid area of ice does not move. By resisting breakup, it stops the movement of the ice that has been broken up on the upstream side....

"c. The third type of jam is rare and occurs only at mouths of major rivers. It is a jam that may form without the presence of large floes and is caused by tidal action. Should the tide be slack, with junk or slush ice in the river, and the temperature be below freezing, the ice will freeze together. When the tide ebbs, the jam will stay in place. This type of jam usually occurs in the Yukon Delta area...."

Henry (1965) provides a description of the characteristics of Yukon River ice jams. During the spring thaw: "... this great frozen mass will start to float downstream, but because of the bends, bars, and other obstructions will not travel very far. The river ice will be in sheets that may be in excess of 1,000 feet long and 200 feet wide.... These sheets will break into smaller pieces, and ice pans of 30 to 40 feet in diameter and 5 to 6 feet thick are common.

"... As they grind into each other, the pressure is sufficient to fuse them into one great mass.... At this time the river flows underneath and no damage occurs. New ice pans arriving hit the jam and are carried under by the current and restrict the flow. Within a short time the channel is blocked and the water rises....

"... The effective dam is not necessarily at the lower end of the ice jam, in fact, it is usually several miles upstream.... The river has many sloughs and is multi-channeled in many places. Where the river is forced into a narrow channel lies the most likely location of ice jams."

Froehle (1966) also comments on ice jams of the Yukon and Kuskowim.

Stothart and Croteau (1965) reported on ice conditions on the St. Lawrence in the Montreal area.

"In the Montreal area, conditions are ideal for the generation of ... sheet ice, frazil and anchor ice. The crystals, or frazil, form in Lake St. Louis and Lachine Rapids and are then transformed into blocks and small rafts in the Laprairie Basin. The blocks then flow unhindered until they reach the calm water of Lake St. Peter, some 60 miles downstream from Montreal. With the colder temperatures of December, the initial freeze-over, or sheet, is formed at the lower end of Lake St. Peter. Once the total ice cover is formed, the new ice flowing downstream comes to rest against the ice bridge and starts an upstream progress of the cover. The backward progress goes on until it reaches an area where the current is too strong to permit its continuance. At this stage, one of two things happens:

a) If the weather is very cold, the ice sheet will be relatively strong and the new flowing ice will plunge under the existing cover to start formation of an inverted or hanging dam. Under this condition, the water level will rise in front of the dam, the current will then drop, and normal progress of the ice sheet resume.

b) If the weather is mild, the ice sheet will not be strong enough to tolerate the increased pressure caused by the flowing ice rafts. The sheet will then buckle or telescope, again starting formation of a dam in restricted areas...."

Hausser (1964) also gives St. Lawrence River ice conditions for the same locality.

The role of frazil ice in the formation of ice jams is briefly discussed by Michel (1963). He mentions blocking of the river channel at Montreal. Small (1955), also describes some ice conditions in the St. Lawrence River.

Ice difficulties in the vicinity of Lake St. Peter are noted by Keefer (1898). He describes the characteristics of some early floods due to ice jams composed primarily of frazil ice in the St. Lawrence River near Montreal. Lea (1924) describes "hanging dams" 60 feet in depth and their occurrence in the St. Lawrence River. Barnes (1926, 1897) notes the formation of ice jams in the Montreal area. Complete blockage of the river by frazil ice at the foot of the Lachine Rapids is reported.

Brown (1957) describes ice jams in the Mackenzie River.

> "The break-up begins at the source and progresses northward downstream. The ice near the mouth, which moves out last, forms a barrier and causes severe ice jams and floods....
>
> In the delta, "... as the water level rises and the current increases, the ice cakes are ground against one another and the shore. Sharp bends in the channels cause jams and the ice may pile up for several kilometres...."

Keefe (1910) as quoted by Kindle (1920) also describes ice jam conditions in the Mackenzie River Basin.

> "In spring, the small side streams are the first to open, then the pressure from the increase of water in the main streams arches the ice sheet and finally breaks it up. The broken ice usually jams at some point lower down, the pent-up water behind the jam breaks out again and sweeps the river clear of ice. This operation is repeated until the entire river is open, no ice being left at the margins."

Harrison (1908) as quoted by Kindle (1920) described the break-up on the Slave River:

> "... In this bend the ice which had broken in mid-stream, got jammed, and during that night the water, in three hours, rose 14 feet. Sometimes, indeed, the ice gets piled 20 feet high in places and seems to be solidly blocked right down to the bottom of the river; for as the ponderous fragments come along, they are drawn in underneath the pack, and it is only when the water has risen in this manner that the stream at length finds outlet and rushes away with a terrific roar...."

MacKay (1961) briefly describes breakup on the Lower Mackenzie River and states that breakup at a seven mile stretch of fast water terminating a mile upstream from Fort Good Hope is delayed by ice jams in the narrow canyon.

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Eurasia

Massive ice jams on the Danube in 1963 are described by Karolyi (1963). Solid ice had developed below the Hungarian-Yougoslav border which later developed into an ice jam at Apatin in Yougoslavia. During the ice jam period, the water underpassed the ice mass and scoured the bottom to a great depth.

Ihrig (1956) and Laszloffy (1948, 1934) also describe ice jam characteristics of the Danube. Von Forgatsch (1947) describes Danube ice jam conditions near Vienna and Pacl (1955) reports on the frequency of ice jams on the Danube in Czechoslovakia.

Siegfried (1957) describes some ice jam characteristics of French rivers.

"...Ice jams begin at many diverse spots and are the result of many causes: this is in general a section enlarged and of shallow depth, of the river, in which the current slackens where the ice accumulates and forms on the banks, such that the accumulation progresses toward the middle of the stream.... The presence of spongy ice facilitates the rapid formation of ice jams upon man made structures.... The ice jam once formed will progress upstream. This upstream progression is generally in a regular fashion and the speed with which it progresses is a function of the amount of ice being transported from upstream. As the ice jam forms the discharge of the river drops rapidly. The conditions of floe and discharge in the river are completely changed....

"Fluvial marine estuaries provide access to important maritime ports (Rouen, Nates, and Bordeaux). The ice problems are different in each estuary and are functions of the discharge of the river and the effects of the tide in the estuary. Hard ice drifts may form in the estuaries particularly at night. This is caused by a lowering of the temperature and a welding together of the ice blocks floating in the estuary. It is possible to attain great thicknesses of ice at low tide. Ice from upstream piles on top of ice that is already in the estuaries. The entire mass becomes stranded at low tide.

"The problem of ice jams in estuaries is particularly seen on the Loire...."

The occurrence and characteristics of ice jams in Latvian Rivers are reported on by Stakle (1936).

> "The three largest rivers of Latvia, the Daugava ..., the Lielupe ..., and the Venta ... flow in their lower reaches through low-lying country where they have deep and broad river beds with a comparatively small fall.... On the other hand there are many rapids in the upper reaches of the rivers further upstream. Enormous masses of anchor- and frazil-ice are formed here in autumn and winter, which confine the river bed, raise the water level and retard breaking-up of the ice in the spring. Spring ice-jams as a rule occur at certain places determined by the river's character and its longitudinal profile, but factors of a coincidental nature also play an important part. Thus almost every year as a rule ice-jams occur in those river districs where rapids pass over into calm water...."

The report continues by describing the accumulation of river ice during the winter and the ultimate ice jams during the spring breakup.

> "... The typical structure of a large ice-jam ... consists of single large and small ice blocks pushed together and cemented with soft frazil- and anchor-ice. These blocks are, however, in a labile state: usually a small force in the correct place is sufficient to bring the ice masses into movement....
>
> "Prior to the general breaking up of the ice, more or less strong sliding movements occur on quiet river stretches. The whole ice cover starts moving and either jams together or pushes itself under the ice cover of the lower reaches....
>
> "The most important causes and locations of ice-jams are the following: First to be mentioned are the quantities and distribution of ice mases in the river prior to ice breaking up....
>
> "A further cause of the formation of jams is a change in longitudinal fall of the river: should ice and water masses carried over rapids at great speed encounter a broad and deep river stretch with a slow current on which the ice cover is firm and has not been lifted and displaced between the river banks, the ice masses are caught, and even if they smash the first part of the ice cover, the floes soon lose velocity and power and come to a standstill....
>
> "An important factor in the formation of ice-jams is the occasion when masses of ice and water from a broad and shallow stretch reach a narrower river bed. A complete redistribution of the floating ice masses is required owing to the changed river cross-section....
>
> "Ice-jams are also caused by islands, shoals, narrows, curves, and structures built into the stream. All of them force the ice and water to change direction, to evade, to repile itself and avoid the obstacle.

A division of the river by islands into several arms acts very adversely on a quiet break up of the ice.

"We should mention also the following incidental circumstances which bring about the formation of ice-jams: 1) formation of ice in autumn at high water level (productive of anchor- and frazil-ice) and 2) the breaking-up of ice in the upper reaches in spring at a time when the lower reaches are still frozen over."

Golek (1957) describes the river ice formation, growth and decay process for Polish rivers. The processes are similar to those noted by Michel (1966) and Laszloffy (1948).

"... With the first appearance of ice phenomena on lakes and rivers, we most frequently observe slush. It begins in very thick masses composed of crystals in needle-like forms and spangles of ice, separated by water.... While flowing, it creates a characteristic appearance of white wreaths, mutually rubbing against each other. In dropping air temperatures, these wreaths begin to freeze and change into ice floes."

"Another ice phenomena of inland waters are the shore ices, which is the first phase of ice cover.

"... Shore icing begins with the formation of crystals and wafers on the edges of stones, rocks and twigs protruding above the water. At the same time, crystals form on the surface of the water, resembling snow. These elements begin to tie in with each other, enlarging and slowly forming a surface.... The last phase of ice cover ends when the waters are covered with this ice, the following phase leading to the thickening of this ice."

"Disappearing ice phenomena on rivers is preceded by break-ups and floating ice floes on rivers. This is because of the changes in water due to thawing.... The appearance of congestions ties in with flowing ice on the rivers. The origin of these congestions are due largely to local conditions.... Favoring these conditions in the corridors of the river are, bridge posts built close together, submerged logs, or sudden thickening of ice cover in river bends, small waterfalls and irregular corridors...."

"In analyzing the appearance of ice congestions on Polish rivers, it was noted that they most often occured on the upper Vistula and its upper tributaries. Favouring these are climate conditions in this region and the ... large and often changing falls, as well as prevailing faults of ice floes in the form of rocky aisles in the river corridors. Observations up to this time indicate that practically every segment of these rivers have a threatening possibility of ice jams occuring especially the segments of inflowing tributaries....

"Segments best known for ice congestions, in all probability occurring 10 to 30% (of the time) are in the vicinity of the Skoczowa River, on the small Vistula River, Ciecina River, on the Soc River, Strozy on the Raba, Waksmunda, Golkowic and Zabna on the Dunaj, Piwniczna on the Poprad. On the Wisloc River below Gawluszowica and its tributaries, the probable occurrence of ice jams amount to 30 to 35%. The San and its tributaries characteristically have great probabilities of ice jams occurring.... Besides profiles mentioned, there exists on the San other inflows threatening segments with probable ice jams occurring 5 to 10%."

"On the upper Vistula, below Zawichost, the best known ice jams occur in the vicinity of Nowa Wsi Popedzynka, Otaleza, Chwalowic and Zawichost (15 to 30%)....

"Some tributaries of the central segment of the Vistula are equally liable to probable ice jams appearing. Ice jams are often noted on the Wieprz River in the Lubartow vicinity. Ice jams often appear on the Bug River, especially in the vicinity of Frankopol, Wyszkowa and Zegrza. Apparently, on the Narwa River, forming of ice jams are often observed on many of its segments, particularly in the vicinity of Siemionow, Narwa and Pultuska. In the Oder River basin, probable appearance of ice jams is noted on the presentation of observations in the year 1936. Regulated work-outs carried on in later years for the Oder, Warta and Notec Rivers unquestionably changed the conditions for ice jam creations....

"Ice jams on the Warta River appear less frequently than on the Oder River. Attention must be directed to the segment between Ostakow (596 km) and Uniejow (481 km), where probable appearance of ice jams can exceed 60% (Kreczow), and the segment between Kolo & Konin where conditions equally exist favouring ice jam origins. In the distant course of the Warta River we observe countless ice jams...."

Popov (1957) describes some characteristics of autumn and spring river ice jams in the U.S.S.R.

"The most important phases of ice regime in rivers are as follows: the appearance of the first drift ice, stoppage in the flow of ice, debacle in rivers and clearance from ice. With the appearance of drift ice, i.e., with the beginning of autumn ice jamming, the navigation and transport by ferries and boats ceases in rivers."

"The autumnal duration of ice jamming in large rivers depends on the intensity of water cooling, the size of rivers, the speed of water current and the volume of water. The more intense the cooling, the sooner the drift ice is formed, the greater is its quantity, the size and thickness of ice floes and, consequently, the sooner the stoppage in the flow of ice will occur. But on the other hand, the larger the river, the more drift ice is needed to be able to stop. Hence it follows that in one and the same river, provided all the other conditions are equal, the duration of ice jamming must be longer in years, when the water discharge is large in the autumn and, vice versa.... Experiments demonstrate that for each river, depending on its water volume, there is a peculiar critical air temperature that is needed for the formation of an immobile ice cover. At a higher temperature, the ice jamming may continue for a long time."

"... The freezing of small and large rivers occurs differently. On small rivers with a slow water flow, the continuous ice cover is most frequently formed by joining of rapidly widening young fast ice along the banks of rivers. Therefore in such rivers there is no drift ice in the autumn....

"Another pattern of freezing is observed in large rivers. Here as a rule, the formation of a continuous ice cover is preceded by a longer or shorter period of drift ice in the fall, which becomes more and more concentrated with the intensification of frost. In sharp bends of rivers in narrow beds and along islands, i.e. where the river is not in a position to let the whole mass of drift ice through, the ice stops. The standing ice floes freeze rapidly together, joining with the arriving floes, and so a continuous ice cover is formed upstream. Downstream of the place of stoppage, rather large areas of open water are not infrequently found where the formation of grease ice takes place.

"... The spring debacle in rivers is affected by two factors -- the thermal and mechanical factors. The thermal action results in the melting of ice. The mechanical action results in the breakup of ice cover and in the disruption of its continuity....

"Mainly, the influence of the heat factor causes the spring debacle in the lower reaches of large rivers such as theVolga, Dnepr and Don. The spring heat in the lower reaches of the rivers occurs considerably earlier than in the main feeding section of the basin....

"A brief spring debacle is observed in large rivers flowing from south to north. The breakup of ice in the rivers occurs in large part as a result of mechanical factors.... The flood wave, moving downstream, raises and breaks the ice when its thickness and firmness are still great...."

Konkina (1957) divides U.S.S.R. rivers into six classes using factors of initial ice formation, autumn ice drifts, complete freeze-up and spring drift.

General information on ice jam characteristics in the U.S.S.R. is also given by Kemmerikh (1958), Panov (1960).

Chishov (1963) classifies the regime of mountain rivers in Central Asia.

"Group I

"1. The ice regime of sections of rivers that freeze over is observed in sections of rivers with low velocities of the currents not exceeding 0.7-1.2 m/sec in the winter low-water period....

"In quiet sections, the growing shore ice soon joins together, forming an ice cover, which reliably protects the water against supercooling....

"2. The ice regime of sections of rivers choked with snow is observed on small water flows with flow rates of the water of less than 1 m^3/sec....

"Group II

"On sections of rivers with flow rates of water of up to 15 m^3/sec, characterized by a fast current, with a considerable heat emission from the water surface as the result of the clogging of the free section by ice within the water, the water saturated with slush flows out onto the surface of the shore ice and the floodplain, which leads to the formation of a unique ice cover, which in this work is called ice layer-ice jam."

"3. The ice regime of sections of rivers with a persistent (stable) ice layer-ice jam ice cover is observed on the small mountain rivers with water flow rates of up to 5-7 m^3/sec, flowing in regions with a severe climate (constant heat emission). On such rivers the ice layer-ice jam ice cover forms at the beginning of winter when the cold snaps set in, and is preserved without any noticeable changes until spring. The formation of intra-water ice is observed only in the period of the formation of the ice cover....

"4. The ice regime of sections of the river with an ice layer-ice jam ice cover subjected to hummocking is observed on larger rivers of the high-mountain belt (constant heat emission) with water flow rates of up to 15 m^3/sec. The hummocking of the ice cover is explained in the following manner. After the shore ice joins together, the flow ceases to lose heat, and therefore the heat liberated because of friction is entirely expended in the melting of accumulations of intra-water ice. Gradually the water level is lowered, and the ice cover turns out to be in a hanging position and collapses over the deep stream. Then the formation of intra-water ice begins anew, as well as the choking of the free section, etc....

"5. The ice regime of sections of rivers with an unstable ice layer-ice jam ice cover is observed on rivers with water flow rates of up to 5-7 m^3/sec, of the medium altitude belt (variable heat emission). An unstable ice layer-ice jam ice cover is preserved only during the freezing period....

"Group III

"On sections of mountain rivers having an adequate transit capability, and on which conditions for the formation of an ice cover are absent, the intra-water ice does not accumulate in the place where it is formed, but moves downstream in the form of slush. On the mountain rivers of Central Asia, according to our observations, the ice regime of sections of the rivers characterized by a slush flow can be subdivided into the following three types....

"6. The ice regime of sections of rivers with a slush of local origin is observed in the upper reaches of mountain rivers.... An ice regime of the given type is formed under conditions of constant and variable heat emission, with flow rates of the water in the section of not less than 6-10 m^3/sec."

"... As a consequence of the small flow of slush the formation of ice jams occurs in rare cases....

"7. The ice regime of sections of the rivers with slush of local and transit origin is characteristic for the middle and lower reaches of large mountain rivers, flowing through regions with severe climatic conditions (constant heat emission). The given type of ice regime is formed as a result of the intensive formation of intra-water ice within the limits of the section, with a considerable flow of slush from the upper reaches; it is characterized by great flow rates of slush and an increase in the flow of slush downstream along the section."

"The considerable heat emission from the water surface and the duration of the freezing period cause an intensive growth of shore ice and ice dams, which, with great flow rates of slush and supercooling of the water leads to the formation of ice jams.

"The process of ice-jam formation on mountain rivers occurs in a peculiar manner. The bed of the river, over the extent of about 10 km, turns out to be filled with a layer of slush deposits, the thickness of which reaches several meters over the ordinary level of the water. After the breaking of the ice jam the masses of slush collapse in many places. As a result, the flow is compressed between the hanging ice banks....

"The processes of ice-jam formation on plains and mountain rivers differ greatly from each other. On mountain rivers, the filling of the open section of the flow under the ice cover (dam) gives a shock for the beginning of the formation of an ice jam, and later on its development is caused by the filling of the zone of the supported section by masses of slush, which then gradually moves upstream.

"8. The ice regime of river sections with slush of primarily transit origin is observed in the lower reaches of large and medium-sized mountain rivers, in the foothill section with a comparatively mild climate...."

> "... Ice dams are observed only on individual sections and not every year...."

Antonov, Ivanov and Nolimov (1964) describe two types of river ice conditions pertaining to ice jams in Arctic areas of the Soviet Union.

> "The first type is common to such rivers as the Yenisey, Lena, and the Kotuya. The opening of them is ... accompanied by violent ice break up with the formation of a large number of mighty ice jams...."

> "During the formation of ice jams, in places favored by the morphologic shape of the river channel (slack waters, around islands, sharp turns, etc.) the usual extent of the zone of mechanical disintegration of the ice, by the flood waves, is limited to the ice drift part, a significant decrease in flow at the expense of stopping the movement of the ice beating in front of the obstacle and filling up the ice jam...."

> The second type "... can be referred to the rivers: Khatanga, Kolema, Indigirka, Olenek, and Yana. On these rivers, in their lower courses, the process of opening does not exhibit so violent a character, as on the Yenisey or Lena. However, in certain years they have sufficiently intensive ice drifts, areas of ice jams and at times exhibit the distinct character of rivers of the first type...."

Laktionoff (1957) also describes Russian river ice conditions. The characteristics and destructive effects of ice jams are described. Ice dams or accumulations of frazil ice cause considerable damage and occur both in southern and northern rivers while ice jams are mainly found on rivers flowing from south to north.

Details of ice jams on the Yenisey River are examined by Liser (1959).

> "One of the distinct features of the hydraulic regime of the Yenisey River is the re-occuring formation of ice jams, which causes severe fluctuations in the water level. At such time, there exists the repeated threat of flooding, and when the jams are accompanied by raging ice drifts, of extensive property damage. Such circumstances inspire comprehensive studies of spring ice jams on the Yenisey River...." Pertinent material is summarized in figures 1 and 2 of Liser's report.

Two additional reports by Liser (1961, 1957) describe ice jamming conditions on the Yenisey near Krasnoyarsk.

Using records from 1887-1957, Bezuglov (1959) analyzed ice jamming on the Neman River. Below the confluence of the Neman and Neris Rivers, ice jams are classified into three groups.

Jams in the middle stretches of the Neman are "caused by the encounter of the ice from the upper stretches with the rigid ice sheet in the lower stretches.... The jamming is further promoted by the fact that on a whole

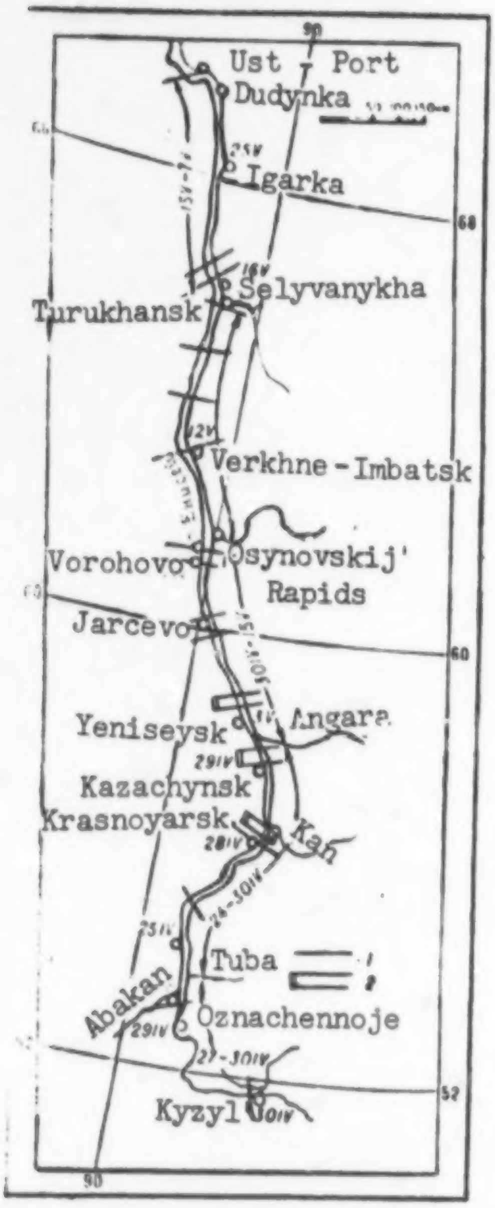
Ust - Port
Dudynka
Igarka
Selyvanykha
Turukhansk
Verkhne-Imbatsk
Vorohovo
Osynovskij'
Rapids
Jarcevo
Yeniseysk
Angara
Kazachynsk
Krasnoyarsk
Kan
Tuba
Abakan
Oznachennoje
Kyzyl
1
2
90
60
68
52

DIAGRAM 1. Average break-up periods on the Yenisey and location of jam centers

1.- jam locations
2.- jam stretches

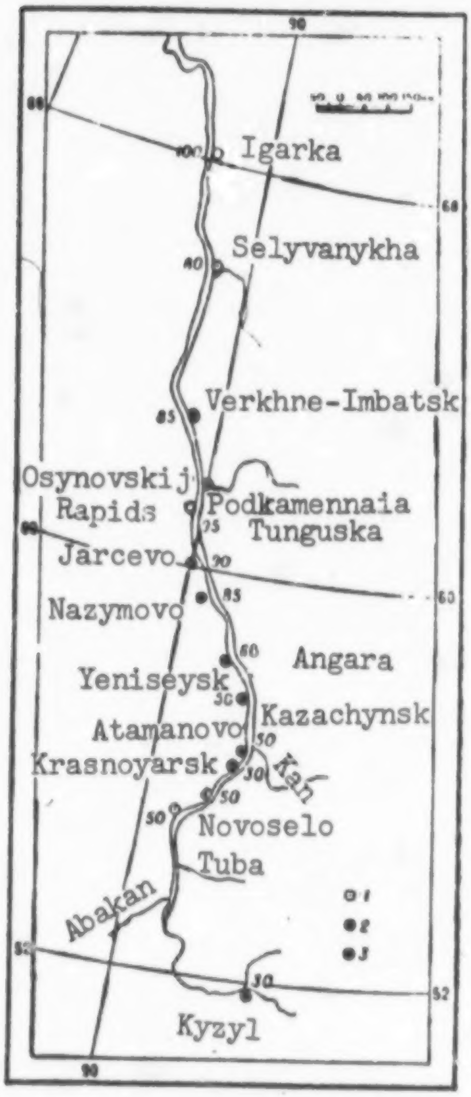
Igarka
Selyvanykha
Verkhne-Imbatsk
Osynovskij
Rapids
Podkamennaia
Tunguska
Jarcevo
Nazymovo
Angara
Yeniseysk
Kazachynsk
Atamanovo
Krasnoyarsk
Kan
Novoselo
Tuba
Abakan
Kyzyl
1
2
3
100
80
85
95
90
85
60
50
50
30
50
50
30
90
60
68
52

DIAGRAM 2. Frequency and intensity of jams on the Yenisey R.

1.- weak jams
2.- average jams
3.- strong jams
(numbers indicate frequency)

(Liser, 1959)

series of points in the middle stretches of the Neman, jams also form annually, and after their break-down produce re-inforcing conditions for a higher level of jamming in the lower portions of the river.... After break-down of the last such jam, the vast masses of accumulated water and ice are discarded in the region of Kaunas and bring about the mechanical break-up of the ice sheet on that stretch. Here, the ice sheet which still remains fairly solid is resistant to the break-up and, at first, moves in large fields (floes). Such floes, striking against obstacles in the channel (islands, shoals, shores on the curves) continue forming larger pile-ups until they reach such proportions that their movement stops, and thus produce favorable conditions for large accumulations of ice continuously being brought in from the upper stretches.

"All this time, the pressure of water on the ice is increased, and finally reaches such strength that the ice floes begin to break into comparatively small sections.... The ice while breaking, revolves, gets into a vertical position, and blocks almost completely the entire 'live section' of the river. Only after all of the ice cover is broken and 'packed' into the jam, does the movement of ice cease, and the formation of the jam completed...."

"The second type of jam results from the earlier breakup in the Neris River while the ice on the Neman River is still fast. The Neris ice discharges under the ice cover of the Neman, without disturbing it to any great degree, and accreation type jams form under the ice."

"The third type of jam occurs when ice from both rivers accumulates in a small area below the confluence. In this case, the Neris transfers its ice in the customary way, under the ice sheet of the Neman; as the ice of the middle Neman produces breakage of the lower-lying ice cover and results in concentration of huge masses of ice on a small stretch, ice jams emerge....

"Out of 60 years, in the course of which jams were observed on the Neman below Kaunas, the first type occured... 48% (of the time), the second ... 40%, and the third type ... 12%...."

"The heat preparation of ice for the breakup can be expressed as the sum of positive average daily air-temperatures passing from 0° to breakup (Σt_+). The breakage force of the stream can be characterized by the degree of water level rise over the mean winter level (ΔH).

"The relative correlation between the heat and mechanical factors of breakup of the Neman River in Kaunas for the three types of ice jams is shown in Table 3.

TABLE 3

Type of jam	Relation $k = \frac{\Sigma t_+}{\Delta H}$
Jams of the middle Neman	0.11
Jams of the Neris	0.11
Combined jams	0.09
Years without jams	0.28

(Bezuglov, 1959)

> "The average coefficient of the heat preparation of ice for breakup (k) for the jam-free years exceeded three times those of the jammed years. The average coefficient for the various types of jams is fairly similar. Coefficients of heat preparation for the years of very intensive jams were very small, on the average of about 0.07."
>
> "Morphological characteristics of the channel, which by some authors, are attributed great importance, do not play a decisive role in jam formation during the conditions described by us."

Balanin and Szcherbakova (1967) describe some characteristics of ice jams in the North Dvina River.

> "... Heavy ice dams form in the vicinity of the towns of Velikiy Ustjug and Kotlas, located in the upper reaches of the North Dvina....
>
> Downstream from Kotlas the river breaks up calmly.
>
> "Ice dams in the lower reach of the river are mostly formed at the points as far as 120 and 60 km from the mouth, as well as in its delta.
>
> "In the first case the ice dams are formed in an unbraided channel of the river, they are broken through very quickly and before the debacle of the delta arms. This is one of the reasons of the ice dam formation in the latter.
>
> "In the second case, ice dams are formed in one of the braided channels, much ice is accumulated there, the destruction of the ice dam goes on very sluggishly and takes place later than the delta arms break up."

Kanavins (1943) describes spring ice jams on the western Dvina while Moskovkina (1956) uses data over a 370 year period to analyze jamming conditions on the river and in Riga Bay. Ice jamming characteristics near Archangel are given by Lopatin (1946) and Zubov and Liakhnitskii (1930).

Sovetov (1938) analyzes the conditions which cause ice jams in the Neva River.

> "The ice on the Neva at Leningrad originates in Lake Ladoga. The ice forms in late autumn or early winter. An east wind breaks blocks of ice from the lake cover and drives the floes into ... the Neva. In the area of Leningrad the ice drifts into the individual branches of the river.... The ice floes increase in intensity in the narrow, winding river, knocking against each other until they grind to a halt in an ice jam.
>
> "When this happens the ice is pushed, by the current, into an inclined mass. Ice particles are also pushed onto the surface and are buried by more ice. Atmospheric cooling ... can freeze the relatively porous ice jam into a solid mass of ice....

> "The formation of ice on the river, with that which is torn from the bottom rises to the river's surface appearing as small ice floes.... These drift until they encounter an ice jam and accreate to the bottom of it, due to the current flow under the jam. Frazil accreates on the underside of the ice in clusters which cling to the sides of the water passage. In this way ice will close off (or at least greatly restrict) the flow of water under the ice...."

Vendrov (1933) describes autumn ice jam characteristics of the Neva using data over a 3 year period. The synoptic conditions preceding ice jams on the Neva from 1881-1923 are analyzed by Loveiko (1927).

Khobta, in a Russian report, (1957) uses data from Kuban River tributaries to analyze a few ice jams in that locality.

> "Ordinarily, in the mountain stretches of the rivers, obstructions that would prevent the downstream movement of frazil ice are lacking. As a result, all of the frazil ice in the river is carried into the foothills or into the populated regions situated downstream where both natural and artificial obstructions create the conditions necessary for formation of accreation ice and ice jams."

In an extensive work on the water resources of the U.S.S.R. Rodevich (1936) summarizes the ice and ice jam characteristics of rivers in the Lena-Yenisey region.

> "An extremely important factor in the winter regime on the Yenisey River is bottom ice, which forms here in great quantities. This is related mainly to the lateness of the freezing up of sections of the Yenisey. Brash ice appears approximately two weeks before freeze up; it comes to the surface from the bottom and contains frozen sand, pebbles and gravel. Because of the powerful formation of this bottom ice on the bars and spits, during the fall ice drift one frequently observes ice jams which result in considerable rise in water levels."

> "The spring ice drift on the Yenisey River... is of a grandiose nature.... There are places where the ice is compressed or the bed is clogged with underwater obstacles, as well as places where the river makes sharp bends, and in these places great ice jams are liable to form causing considerable rises in water levels on those sections of the river above the jam points."

On the Tuba River: "The spring ice drift is boisterous and frequently is accompanied by ice jams in the bed which last for almost seven days. The rise in the level from the moment of opening up takes place in the form of a number of increasing peaks, among which are the ice jam peaks."

On the Tunguska: "The streams, usually with little water in them in the winter time, during severe winters freeze solid and, in the spring, the ice carries large rocks which have been frozen in the ice and those rocks, together with the ice and waters of the Tunguska River are carried further and jam up...."

"The ice drift on the Lower Tunguska River is of grandiose proportions.... The collosal strength of the ice drift can be seen in the polished rocks along the bank area, the huge stones carried by the ice over great distances and furrowed by the ice, in the tree torn out by the roots and the driftwood, deposited in vast quantities in the shrub belt of the sloping beaches. After the passage of the ice the river level rises everywhere."

On the Angara River: "Because of the great speed of the current, as well as because of the considerable unevenness of the bottom, the process of formation of bottom ice here takes on such proportions that individual sections of the river are in no condition to pass the entire mass of sludge which floats up from the bottom and this mass tightly blocks the free flow of water in the bed. Because of this, sections which are located above such ice dams as these get a reduced flow, and the sludge which floats in the water in such sections freezes into a common mass, forming the surface ice cover. In this way, the sludge jams facilitate the covering of the river surface with ice. As one such jam forms, there is the immediate beginning upstream on the river of the formation of new jams....

"Occasionally this scheme of things is interrupted because of sudden heating of the air, or of the water, and, as a result, the ice masses begin to move with the current. Small ice movements, usual on the Angara, just facilitate the compacting of the sludge mass, if only because such movements do not go beyond the boundaries of the individual sections of the bed which are dammed up by the ice jams.

"The jams which form are unstable masses of accumulated sludge, easily punctured by ski poles, for example, and therefore, the jams are not very firm. Even before their formation is complete they frequently begin to fall apart.

"Rivers currents gradually wash out the sludge mass, forming jams, and wherever this washing action occurs it can easily be recognized by the noise and the battering of the ice which is floating under the surface layer of the jammed section of the bed.

"On the Angara River jams occur in those places where the free flow of the sludge into the river bed is impeded, at individual islands, or groups of such islands, on shoals, at sharp bends, around rocks, etc."

The Kitoy River "... usually opens up at the end of April to the beginning of May and freezes from the end of October to mid-November. Freezing here ... is ... accompanied by the formation of ice jams resulting from brash ice formations...."

On the Oka River: "The particularly heavy ice formations are confined to those areas where indigenous rocks extend out into the bed of the river and are not covered by layers of alluvial deposits.... Because of the sharp bends which the river makes in this area there are ice jam formations, in connection with which individual sections of the ice cover on the river are frequently hummocky belts extending for distances of several kilometers."

In the Lena River: "Ice jams and blockades on the Lena River attain exceptional importance because of the northern trend of the river and the sharp compression of the bed by the banks along some sections of the river....

"The comparatively short spring ice drift along the Lena River is sometimes accompanied by major catastrophies in connection with the great rises in levels resulting from the ice jams and the castastrophic breaking up of these jams which back up masses of water.... The breaking up of the ice jams results in vast destruction of the banks and to formations. During periods of ordinary spring ice drift whole islands are cut out, shoals are destroyed and destruction of parts of the bed result from rock debris action."

"The Mana River a right tributary of the Yenisey, has strong currents over many of its sections, as a result of which the bottom ice formations are a powerful phenomenon on the river. Ice jams are abundant here, raising the water level. There are many hummocky sections, but there are, as well, smooth sections of ice cover on the quiet reaches. There are individual sections containing rapids... which freeze only in very severe winters, but even then only as a result of the formation of ice jams of sludge which occur because of the reduction in the current velocity and the attendant possibility of the sheets of floating sludge ice freezing into the surface."

Additional aspects of ice jamming on the Angara are given by Gotlib, Zaimin and Smolin (1959, 1957).

According to Kravchenko (1959) ice jams on the Dniestr River can extend over more then 100 km. Shoals in both banks, deep water in the middle of the river, and a decreased slope in the reach combine to promote ice jamming. Anchor ice can form ice jams.

Mashukov (1957) describes ice bridges and dams on the Syr Darya River from aerial reconnaissance during a 7 year period.

Balashov (1958) found, from data over a 23 year period, that ice jamming is intense in the lower Ponoi River. The upper and middle reaches are free from ice jams.

Meanders in the upper Ural caused ice jams as noted by Filin (1933).

Ramazan (1954) studied ice conditions in 865 small rivers at elevations up to 4 km.

Eurasia

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Ice Jam Effects

The destructive effects of ice jams are usually widely publicized. High water levels sometimes periodically threaten to flood entire cities. Damage by the ice itself is confined to riverside industries, dwellings, and in-river structures.

Descriptions of damages to structures are usually of a non-technical nature and can be obtained from local news media. The following discussion is confined to water level variations and erosion and sedimentation caused by ice jams.

Effect on water levels

Livshits (1961) describes the causes of water level fluctuations due to ice jams.

> "The maximum rise of water levels immediately above the jam basically depends on the character of the channel and the river valley at the point of the jam, the narrowing and rising of the ice in the river, and the presence of a strong ice cover--and its thickness; the intensity of ice drifts; the velocity of the ice approaching the jam; the water level under the ice below the jam; the intensity of growth of the flood crest to the formation of the jam and after its formation; and from the weather in the period of the jam's formation."
>
> "... A sharp rise in river water levels can occur as a result of an ice jam or the formation of an ice stopper (cork) of frazil."

Shulyakovskii (1963) developed a method for forecasting river stage in the presence of an ice jam.

> "It should be noted that a technique of forecasting maximum ice-jam water stages has been successfully obtained, till now, only for river stretches where ice jamming is due to a general decrease in the river slope.
>
> "For such conditions the main factors determining the maximum stage rise, ΔH_m , over the pre-jamming stage at a given point upstream from the ice jam ... can, for the purpose of obtaining a forecasting technique, be summarized as follows:

1) the thickness of the ice cover on some river stretch from which ice arrives to the given ice-jam stretch, h_{ic} ;

2) the depth of the snow cover on the ice (and in the basin), h_{sn} ;

3) the rate of water stage rise before the beginning of ice pushes or before the beginning of the ice-jam stage rise, i ;

4) the ratio of the total heat input per unit surface of the snow-ice cover in the region of ice jamming (Σq_{in}) to the total heat input per unit surface of the snow cover in the region of flood formation during ice jamming (Σq_{w});

5) the onset of a negative air temperature in the ice-breakup period (θ_{-})

"In general, the following should also obviously be taken into account:

6) the character of the ice cover on the expected ice-jamming stretch (I).

"If large tributaries flow into the ice-jam stretch of a river it is necessary to introduce in the calculation also:

7) the difference between the time of breakup on the main river and of its large tributaries, which flow into the given river stretch (Δt).

"Thus, it is possible to assume that

$$\Delta H_{m} = f\left(h_{ic}, h_{sn}, i, \frac{\Sigma q_{in}}{\Sigma q_{w}}, \theta_{-}, I, \Delta t\right). \qquad (1.VII)"$$

"It is not always possible to say beforehand which factors, for example of those involved in equation (1.VII), are the determining ones for a given stretch and should be introduced in the forecasting method, and which are those whose influence can be neglected. This should be checked by analyzing the corresponding observation data.

"We give below, as an example, the technique of forecasting the maximum ice-jam water stage of the Tom River at the town of Tomsk.

"Ice jams at the time of breakup of the Tom downstream from Tomsk are observed every year, but the maximum ice-jam water stage varies within wide limits- from 497 cm (1944) to 1103 cm (1947) above the zero-line of the graph plotted at the gaging site near the town of Tomsk.

"Here, ice jamming is due to climatic conditions, intensive formation and propagation of the flood wave from the upper and middle mountainous parts of the basin and to the morphological properties of the river bed which favor ice jamming. The basin of the Tom River extends from the south-southeast to the north-northwest. This is also the general direction of river flow. All the upper part of the basin, approximately to the town of Novokuznetsk, and the right-hand bank, farther downstream almost to the town of Kemerovo, is mountainous in character. The catchment basin up to the town of Tomsk has an area of 57,290 km^2. Islands are situated on the Tom River below the town of Tomsk; somewhat more downstream, in the region of the village of Beloborodovo, the general slope of the river considerably decreases.

"There are no large tributaries on the given stretch; thus Δt is not one of the determining factors.

"Since there is a considerable general decrease in the slope on the given river stretch and no winter ice breakups occur there, the ice-cover characteristic on the ice-jamming stretch, I, need not be included amongst the determining factors. This is confirmed by a joint analysis of the observations data for the water stage during freezing and ice jamming in the period of ice breakup and data on the character of the freezing and measurements of the ice thickness on this stretch.

"The remaining factors in equation (1.VII) should, in accordance with the physiographical conditions, considerably influence the value of ΔH_m. Let us verify this by comparing (by plotting graphs) the annual values of ΔH_m with the annual values of each of these factors. Such a verification confirms the conclusion.

"Thus, we assume for the Tom River at the town of Tomsk

$$\Delta H_m = f\left(h_{ice}, h_{sn}, i, \frac{\Sigma q_{in}}{\Sigma q_w}, \theta_-\right). \qquad (2.VII)$$

"A negative air temperature at the time of ice breakup does not occur every year but only in some cases. The influence of θ_- is therefore taken into account in the form of corrections to the values of ΔH_m, obtained from

$$\Delta H_m = f\left(h_{ice}, h_{sn}, i, \frac{\Sigma q_{in}}{\Sigma q_w}\right). \qquad (3.VII)$$

"Owing to the absence of sufficient data on the ice-cover thickness h_{ic} for a given river stretch we take it approximately proportional to the square root of the sum of mean-diurnal negative air temperatures, using the well-known formula ($h_{ic} = m\sqrt{\Sigma\theta_-}$) In this case we determine the quantities $\Sigma\theta_-$ for the period from the beginning of the stable ice formation to January inclusive, since for the Tom River at the town of Tomsk, according to the laws governing the growth of the ice cover, the values of ΔH_m were found to be somewhat more closely related to $\Sigma\theta_-$ during this period than to $\Sigma\theta_-$ during other periods, also during the whole stable-ice period.

"From the values of H_{ic}, obtained from ice courses taken by the west Siberian branch of UGMS on the Tom River from village of Polomoshnoe to the town of Tomsk (during 9 years), the mean value of the coefficient m of $\sqrt{\Sigma\theta_-}$ was found to be 1.8 cm degrees$^{-0.5}$.

"The mean rate of the stage rise at the Tomsk gaging site, during a period from the beginning of a rise of approximately 10 cm per day to the beginning of a sharp stage rise due to ice jamming ($i = \frac{\Delta H_{ic}}{t}$), was taken as a characteristic of the rate of rise of flood intensity before breakup, i .

"We express the relationship between the amounts of total heat input per unit surface of the snow-ice cover approximately by the ratio between corresponding sums of positive (mean-diurnal) air temperatures at the meteorological stations Tomsk ($\Sigma\theta_t$) and Kondoma ($\Sigma\theta_k$), situated in the upper part of the basin, during the period from the beginning of melting until ice breakup.

"Thus, we have to find the relationship

$$\Delta H_m = f\left(\sqrt{\Sigma\theta_-},\ h_{sn}\ i,\ \frac{\Sigma\theta_t}{\Sigma\theta_k}\right). \qquad (4.\text{VII})$$

"Observation data show that the dependence of ΔH_m , for each factor of equation (4.VII) can be taken as a linear function. This makes it possible to solve equation (4.VII) by the least-squares method.

"Not having data for a reliable determination of the dependence of the annual values of the factor m on the factors determining it, we assume it constant. In this case, the final result of the calculation of ΔH_m does not depend on the numerical value taken for it.

"Analysis of the graphs for ΔH_m and their variables shows that cooling causes an additional rise in the water stage, if it begins before the ice breakup on the Tom River in the region of the main center of ice jamming downstream from the town of Tomsk, and not earlier than one day before ice breakup at the town of Tomsk, and if the mean-diurnal air temperature was lower than -1.5°. Such conditions and, accordingly, an additional stage rise in the period from 1928 to 1958 were observed in 6 years (1935, 1947, 1948, 1950, 1956, and 1958).

"Then, from observation data for the period from 1928 to 1958 (25 typical years), excluding data for the above 6 years with temperature drops, we find the numerical expression for equation (4.VII) by the method of least squares:

$$\Delta H_m = 12.09 \sqrt{\sum \theta_-} + 5.48I + 2.76h_{sn} - 71.4 \frac{\Sigma \theta_t}{\Sigma \theta_k} - 7, \qquad (5.\mathrm{VII})$$

where ΔH_m is the maximum water-stage rise during ice jamming over the prejamming stage (in cm) according to the gaging site near Tomsk; I is the mean rate of stage rise at the town of Tomsk from the beginning of a rise, approximately by 10 cm per day, until the beginning of a sharp rise in the stage due to ice jamming, in cm/day; $\Sigma\theta_-$ is the sum of the mean-diurnal negative air temperatures from the beginning of the stable ice period to 31 January; h_{sn} is the mean of the maximum snow-cover depths in the shore area of the Tom River basin on the stretch Polomoshnoe-Tomsk before the beginning of melting (according to snow-course data), in cm; $\Sigma\theta_t$ is the sum of the mean-diurnal positive air temperatures according to the Tomsk meteorological station during the period from the beginning of melting until the ice breakup on the Tom River at the town of Tomsk (without the air temperature in the breakup day and 2 days before ice breakup); $\Sigma\theta_k$ is the sum of the mean-diural positive air temperatures during the same period according to the Kondoma meteorological station.

"We use (5.VII) to calculate the values of ΔH_m for the above-indicated cases when a cooling which caused an additional rise in the water stage was observed. Subtracting the calculated values from the actual figures for ΔH_m , we obtain the values of the additional water-stage rise due to cooling, $\Delta(\Delta H_m)$. For each of these cases we find from the observation data the lowest of the mean-diurnal air temperatures θ_- during the time from the first day before ice breakup on the Tom River at the town of Tomsk until ice breakup on the Tom River in the region of the village of Beloborodovo (in the area of the main center of ice jams).

"From the values found we obtain the graph of the relationship (Figure 104):

$$\Delta(\Delta H_m) = f(\theta_-). \qquad (6.\mathrm{VII})$$

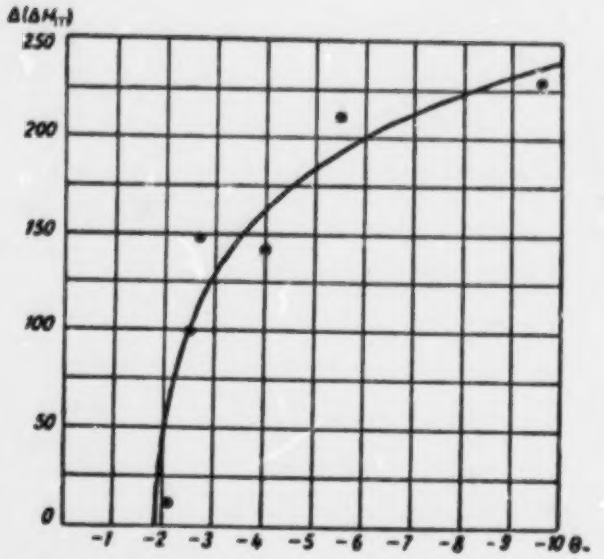

FIGURE 104. Additional stage rise at the time of ice jamming on the Tom River at Tomsk $\Delta(\Delta H_m)$, as a function of the lowest of the mean-diurnal air temperatures, θ_-.

(Shulyakovskii, 1963)

"When preparing a forecast of the maximum ice-jam water stage H_m , the correction for the cooling during the breakup period $\Delta(\Delta H_m)$ to the maximum ice-jam water-stage rise, ΔH_m , calculated by equation (5.VII), is determined from the graph in Figure 104.

"The forewarning period for the Tom River at the town of Tomsk amounts on the average to 4 days, decreasing in a number of cases to 1 day and increasing to 11-12 days.

"The forewarning period can be increased by predicting the daily water discharges or by introducing into the calculation instead of the rate of water stage rise, its determining factors."

Bajorunas (1963) investigates the effects of ice jams on water levels of the Great Lakes. Flow reduction by ice jams in the St. Clair and Detroit Rivers is shown to be reduced by up to 80,000 cfs. under extreme conditions. First, relationships are derived between change in lake level and outflow from the lake.

"The change in volume of water in a lake is equal to the water surface area A of the lake multiplied by the change in water level dS, and is also equal to the excess of the constant inflow I over variable outflow Q during a time period dt.

$$AdS = (I - Q)\, dt \tag{5}$$

Multiplying both sides by dQ and rearranging

$$dQ / (I - Q) = (dQ / AdS)\, dt \tag{6}$$

Integration within the limits of time zero and t and the limits of outflow Q_0 and Q gives:

$$Q = I - (I - Q_0)\, e^{-\int_0^t (dQ / AdS)\, dt} \tag{7}$$

The above equation gives outflow at any time when the stable conditions (inflow equal outflow) were disturbed changing the inflow from I_0 to I. Although simple in appearance, the equation is rather difficult to solve exactly. An approximate solution is made more enticing by the fact that the integer dQ / AdS changes rather slowly with the stage, since it consists of the water surface area and the slope of the discharge rating curve. Its average value can be used within certain limits, which depend on the required accuracy of the results. Any degree of accuracy can be obtained by the successive approximation method.

"The preceding general relationships can be simplified when applied to the Great Lakes.... Consider a single factor which will change the inflow by i and the outflow by q such that

$$i = I - I_0 \tag{8}$$

$$q = Q - Q_0 \tag{9}$$

"The variation of water area in the Great Lakes caused by water level changes is rather small and is less than the accuracy of the basic data, such as flow measurements, and therefore can be neglected. Further the water level changes are very gradual and can be ignored in investigations covering short periods. This is also done for investigations of some future effects since the lake levels are not known. In all other cases observed levels must be used since mathematical relations are obscured by other factors. For example, an ice jam in an inflow river as a single factor would reduce the level of a downstream lake; however, frequently that level will go up due to increased water supply from snow melt.

"For the Great Lakes the following relationship is most useful:

$$q = i\,(1 - e^{-kt}) \tag{10}$$

where

$$k = \left[\, a\, m\, (S - b)^{m-1} \right] / A \tag{11}$$

and the S represents the mean water level during given period (a, b and m are constants derived from flow measurements).

"Going one step further, consider the regulation effects of two lakes connected by a river having insignificant storage capacity. Again assume a constant inflow change into the upper lake. Let q' be the variable change in outflow from the upper lake and q" from the lower lake.

Equation (6) can be modified to give

$$dq'' = k'' (q' - q'') dt \tag{12}$$

Substituting for q' its value from equation (10), integrating and rearranging in convenient form

$$q'' = i(1 - e^{-k't})k''/(k'' - k') - i(1 - e^{-k''t})\, k'/(k'' - k') \tag{13}$$

"Effects of variable change in inflow

"The simplest example of variable change is when a constant inflow change is discontinued after a certain time. In this case, the effect on the outflow is the difference between outflows from two constant inflow changes, one starting at zero time with i, and the other starting at t_1 time with -i.

$$q_t = i\,(1 - e^{-kt}) - i\left[1 - e^{-k(t - t_1)}\right] \tag{14}$$

or rearranging

$$q_t = (q_{t_1} / e^{-kt_1})\, e^{-kt} \tag{15}$$

The above equation indicates that when the change in inflow is discontinued, the change in outflow from a lake gradually decreases, and that decrease is proportional to e^{-kt}. The proportionality factor q_{t_1}/e^{-kt_1} is constant and is defined by the outflow change at the time the inflow change was discontinued.

"Any additional change in inflow can be considered as a new change and added to the effects of the previous changes. However, such a procedure is convenient only for a limited number of inflow changes. When the inflow variation is frequent or continuous, the routing method must be used. Equations can be derived to make that routing rather simple.

"For this purpose, consider two equal periods ($t = 1$) with two inflow changes, i_1 and i_2. The change in outflow at the end of the first and second periods, respectively, will be:

$$q_1 = i_1 (1 - e^{-k}) \tag{16}$$

$$q_2 = i_1 (1 - e^{-2k}) + (i_2 - i_1)(1 - e^{-k}) \tag{17}$$

Inserting equation (16) into (17) and rearranging, the following is obtained:

$$q_2 = q_1 + (i_2 - q_1)(1 - e^{-k}) \tag{18}$$

Equation (18) is the routing equation for the variable change in inflow. To solve that equation, all that is needed is the outflow change at the end of the previous period (regardless of what inflow changes caused it) and the current inflow change. This routing is a continuous procedure, and it is impossible to delete any steps; however, if the inflow change is discontinued, equation (15) can be used to shorten the computation.

"Practical application

"... Two years were selected having extreme flow retardation in the St. Clair and Detroit Rivers by ice-jamming.

"Ice retardation is the difference between what the flow would have been under open water conditions and the actual flow in these rivers. This presumes that within certain limits the magnitude of ice retardation does not depend on lake level. The ice-jamming reduces the outflow from Michigan-Huron and raises its level and at the same time reduces inflow to Erie and lowers it. These effects are computed in Table 2. The rise in the Lake Michigan-Huron level is moderate; however, most of it is retained for the next ice season, so the ice effect accumulates until it reaches a certain value which varies slightly from year to year. Computations in Table 2 assumed zero ice effect at the beginning; therefore, they do not show the actual magnitude of water level and outflow changes. The Lake Erie level is lowered much more; however, this lowering dissipates quite rapidly and it is almost gone when the new ice season begins."

Table 2. Effects of Ice-jamming in St. Clair and Detroit Rivers (Bajorunas, 1963)

YEAR MONTH	FLOW REDUCTION BY ICE 100 CFS	LAKE MICHIGAN-HURON			LAKE ERIE			
		Increase in outflow		Lake level rise	Inflow change	Decrease in outflow		Lake level lowering
		End of month 100 cfs	Monthly mean 100 cfs	ft	100 cfs	End of month 100 cfs	Monthly mean 100 cfs	ft
1904 D	150	4	2	.01	-148	27	14	.06
1905 J	800	27	16	.12	-784	167	97	.45
F	730	46	36	.26	-694	265	216	.99
M	380	56	51	.37	-329	277	271	1.25
A		54	55	.40	55	215	246	1.13
M		53	54	.39	54	166	190	.87
J		51	52	.38	52	125	146	.67
J		50	50	.37	50	93	109	.50
A		48	49	.36	49	67	80	.37
S		47	48	.35	48	45	56	.26
O		46	46	.34	46	28	36	.17
N		44	45	.33	45	15	22	.10
D	200	49	46	.34	-154	41	28	.13
1906 J	250	54	52	.38	-198	70	56	.26
F	490	67	60	.44	-430	137	104	.48
M	560	80	74	.54	-486	202	170	.78
A	430	90	85	.62	-345	229	216	.99
M		88	89	.65	89	169	199	.92
J		85	86	.63	86	122	146	.67
J		83	84	.61	84	84	103	.47
A		81	82	.60	82	53	68	.31
S		78	80	.58	80	28	40	.18
O		76	77	.56	77	8	18	.08
N		74	75	.55	75	- 7	0	.00

Based on 12 month mean level the factor $(1 - e^{-k})$ for M-H is 0.0281, 0.0281, for Erie is 0.185, 0.186.
Lake level change M.-H. = 0.0073 q, Erie = 0.0046 q.

Simojoki (1952) developed two methods of determining water level fluctuations due to ice jamming.

"The present investigation was undertaken to shed light on the effect of river level rising at ice break-up time and to examine water level rising caused usually by ice jams."

"Table 2 gives the average data respecting the beginning and ending of ice break-up, A_1 and A_3 respectively. Table 2 also gives the average differences A_1 --T_0 between the spring o^o -isoterm and A_1, the said values varying from 8 to 16 days....

"The variations in water level during ice break-up were studied as follows. First, the daily water level readings for different years were grouped according to time of beginning of ice break-up A_1, and then the averages for water level in the neighborhood of A_1 were computed for different days. The obtained values represent the average course of water level, thus relating to the one and same phenomenon and not to the mean value computed for the calendar year.

"Diagram 2 ... shows an abrupt rising of water level before the beginning of ice break-up. During ice break-up irregularities mainly caused by ice jams appear. After the elapse of time A_3 for disappearance of ice, the variation water level course is regular. The same facts are revealed in Table 3, where the average differencies (sic) $h_n - h_{n-1}$ of water level for consecutive days are given instead of the water level values. The table shows also the total rising of water level during springtime as computed from the water level h_{-20} twenty days before A_1 to the maximal spring water level h_{max}. The lower limit h_{-20} is, of course, arbitrary, but may be used in this introductory investigation because the variation in water level on the whole is slight during this time.

"In general the difference $h_n - h_{n-1}$ increases until the beginning of ice break-up, subsequently reaching its maximal value; later on it becomes negative. The considered observation period is too short to allow detailed comparisons. The irregularities may originate to some extent, from uncertainty in determining the phase A_1 which fact in part influences the grouping of water level values. In Putaanjoki $h_n - h_{n-1}$ reaches its maximum before the phase A_1."

"Table 3 shows that in many rivers there is, in the beginning of ice break-up, an abrupt increase of the difference $h_n - h_{n-1}$, which mainly depends upon the jamming effect of ice. In the following an attempt is made to estimate the rising of water level caused by ice jamming by using the water level observations for this purpose.

"To determine the jamming caused by ice a graphic analytical method was used. The water level curves for each spring were drawn separately and the abrupt water level risings occuring during the time of ice breakup

Table 2. The average data (April) for beginning and ending of ice break-up respectively A_1 and A_2 as also the average time from the 0°-epoch T_0 to the phase A_1.

Observation place		A_1	A_2	$A_1—T_0$	Place for temperature observations
Kemijoki	(1)	39	45	15	Sodankylä
»	(2)	36	44	13	»
Iijoki	(3)	31	42	16	Oulu
Kiiminginjo'd	(4)	26	36	11	»
Lestijoki	(5)	23	26	13	Vaasa
Kyrönjoki	(6)	24		13	»
»	(7)	22	24	11	»
Loimijoki	(8)	17	21	8	Tampere
Kokemäenjoki	(9)	12	21	10	»
»	(10)	14		10	»
Putaanjoki	(11)	11			
»	(12)	9		11	Turku
»	(13)	7			

Table 4. Average jamming in cm during ice break-up.

River		Before A_1																		A_1	After A_1					
		18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	1	2	3	4	5	6
Kemij.	(1)					1	2	3	3	3	4	4	4	3	5	3	5	11	29	38	*70*	33	35	13	9	5
Kilminginj.	(4)																1	7	13	*32*	13	1	2	3	2	
Lestij.	(5)			4	10	11	10	6	4	2	2	2	4	5	5	4	4	4	8	20	32	*42*	8	4	2	1
Kyrönj.	(6)	7	8	8	9	6	7	8	7	7	6	6	10	9	10	10	11	10	11	*14*	10	8	4	4	4	3
Kokemäenj.	(9)	4	4	5	6	6	6	7	7	6	5	4	7	7	5	4	5	7	9	15	*25*	16	17	13	10	5
Putaanj.	(11)	4	3	6	9	14	18	17	19	*22*	*22*	20	12	5	5	14	5	7	1							
»	(12)	4	11	10	9	7	6	6	7	5	5	7	11	*12*	*12*	7	6	6	3	6	4	3	1			
»	(13)	3	5	3	3	2	1	1	4	3	1	2	2	4	*6*	3	4	*6*	*6*	3	1					

Table 5, which contains the average and extreme values for maximum jamming, gives a clear picture of the order of jamming.

Table 3. The average differencies $h_n—h_{n-1}$ in cm during ice break-up.

River		Before A_1										A_1	After A_1										$h_{max}-h_{-20}$	
		10	9	8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8	9	10		
		$h_n - h_{n-1}$																					Average	Max
Kemij.	(1)	0	7	2	2	3	6	4	6	14	16	24	*39*	—39	6	—13	1	—2	1	3	3	1	186	312
Iij.	(3)	2	3	—1	1	1	4	6	14	2	-2	*13*	12	7	8	10	2	1	4	1	6	5	149	252
Kiiminginj.	(4)	0	0	0	1	1	2	4	9	11	12	*27*	2	6	9	5	1	—1	—2	—2	0	—1	137	210
Lestij.	(5)	1	3	1	5	7	10	13	14	18	21	23	*33*	10	—31	—11	—6	—15	—13	—11	—6	—6	195	319
Kyrönj.	(6)	10	9	10	10	5	9	12	*15*	*15*	9	12	0	—5	—1	—4	—24	—4	—5	—6	—8	4	172	362
Loimij.	(8)	1	3	4	0	1	2	4	8	11	*12*	11	0	—3	—3	—1	0	—10	—4	—9	6	—1	93	202
Kokemäenj.	(9)	0	2	1	6	4	1	1	4	7	5	8	19	—5	9	—3	—5	—7	—4	—3	—5	—1	97	306
Putaanj.	(11)							2	*11*	9	3	6	3	5	—1	0	—8	—9	—4					
»	(12)				8	5	6	—3	5	*10*	4	7	—5	—9	—8	—10	—7	—9	—7					
»	(13)		3	3	2	*4*	2	*1*	*1*	3	0	—4	—4	—4	—2	—3	—5	—4	—1					

Table 5. The average maximum values of the jamming during ice break-up and its extreme values in cm. K on using curve analysis, D on using difference method.

River		Maximum jamming			
		Average values		Extreme values	
		K	D	K	D
Kemij.	(1)	110	127	212	322
Kiiminginj.	(4)	39		121	
Lestij.	(5)	63		125	
Kyrönj.	(6)	38	50	125	132
Kokemäenj.	(9)	39	43	165	159
Putaanj.	(11)	38		86	
»	(12)	33		57	
»	(13)	15		22	

(Simojoki, 1952)

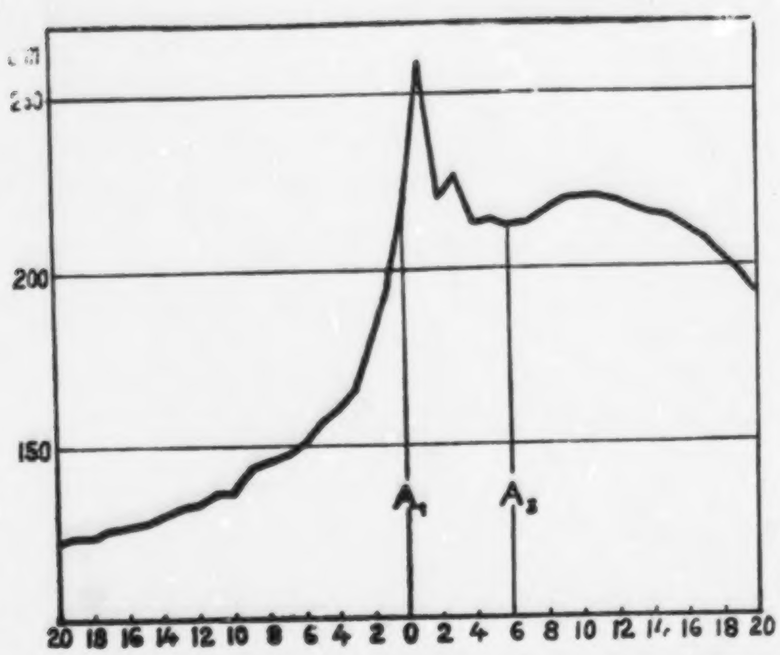

Figure 2. Mean water level course during ice break-up at Kemijoki, Rantaniemi. A_1 the beginning, A_2 the ending of ice break-up. (Simojoki, 1952)

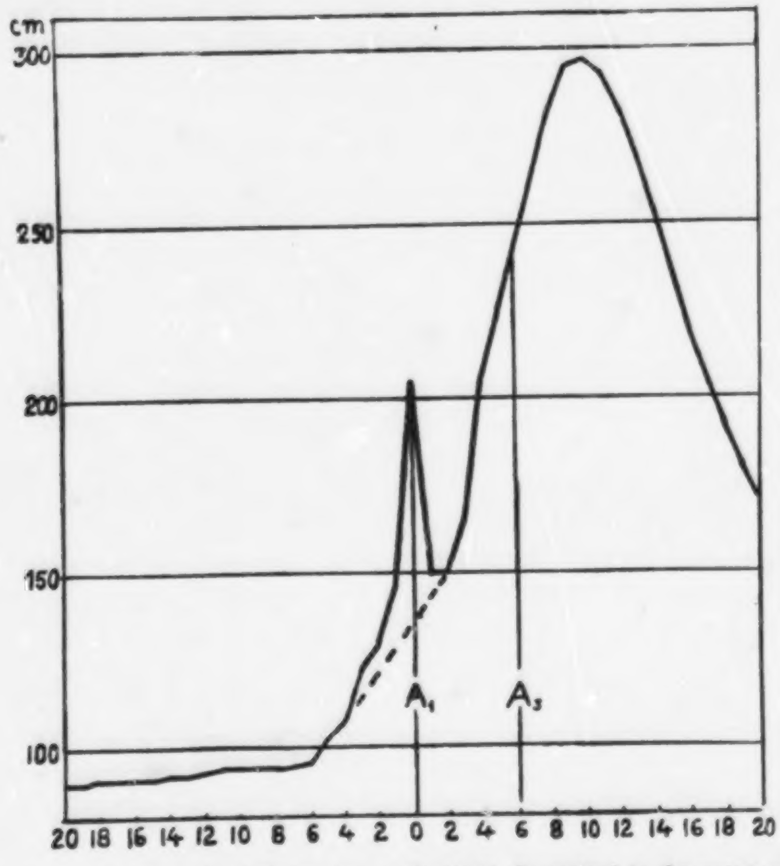

Figure 3. The water level fluctuations at Kemijoki, Rantaniemi in the spring 1923.
(Simojoki, 1952)

were explained as having been caused by ice jamming. The determination of jamming of ice in the spring of 1923 for the tide-pole at Kemijoki, Rantaniemi is illustrative in showing this method (Figure 3). On the solid curve obtained for water level an area separated by using a broken line is assumed to be dependent upon ice jamming. Should jamming last a short time and the rising of water level be abrupt, this method may be used for the approximate determination of jamming. If, on the contrary, the rising of the water level is slow, the determination of jamming may be rather uncertain. The result of the method will therefore depend considerably upon subjective circumstances.

"The analysis results of the water level curves are tabulated in Table 4, which presents the average distribution of jamming about the period of time for ice break-up. In the rivers of large drainage areas the maximum was generally reached during the first or second day of ice break-up....

"Table 5, which contains the average and extreme values for maximum jamming, gives a clear picture of the order of jamming.

"To verify the results obtained, jamming was determined according to another method not dependent upon subjective circumstances and based upon observations made simultaneously on two water level tide-poles in the one and same river.

"Suppose that the difference between water level readings on tide-pole h' observed during two consecutive days is represented by $h'_n - h'_{n-1} = \Delta'$ and that the difference between water level readings on another tide-pole h" in the one and same river is correspondingly $h''_n - h''_{n-1} = \Delta''$. The difference $\Delta' - \Delta''$ will then express the order of jamming on the assumption that a variation in river water quantity causes the same deviation on both tide-poles. If jamming occurs at the lower situated tide-pole while the runoff higher up is undisturbed, the difference $\Delta' - \Delta''$ will denote jamming at the lower tide-pole. If, on the contrary, jamming occurs at the higher up situated tide-pole with no disturbance at the lower tide-pole the difference $\Delta' - \Delta''$ will represent jamming at the higher tide-pole in comparison to the lower one. However, the value obtained will be too large because the water level at the lower tide-pole has decreased in consequence of the influence of jamming higher up.

"Generally, as the tide-pole profiles in reality differ from each other, the correction caused by this fact was determined as follows: A comparison curve for the water levels of the tide-poles h' and h" was drawn for the time of high water. h" and h' were selected respectively as abscissa and ordinate for the comparison curve. The comparison curve may approximately be substituted by a line whose angle coefficient $tg\,\alpha$ is the correction factor caused by the shape of river bed. Jamming may then be computed upon application of the formula

$$\Delta_1 = \Delta' - tg\,\alpha \cdot \Delta''.$$

When $\Sigma\Delta_1$ is computed the jamming during a definite period of time will be obtained.

"The latter method is illustrated in Figure 4, which presents the average course of Δ_1 at the Rantaniemi tide-pole in Kemijoki during the time of ice break-up as computed by application the formula $\Delta_1 = \Delta_R - 0.7 \cdot \Delta_T$. In this connection Δ_R and Δ_T denote the average changes in water during consecutive days for the tide-poles respectively at Rantaniemi and at Taivalkoski. Before the phase Δ_1 jamming was noted at the Taivalkoski tide-pole $\Delta_1 < 0$. On the first and second day of ice break-up $\Delta_1 > 0$, which denotes jamming at the Rantaniemi tide-pole. Later on Δ_1, decreased abruptly and becomes negative. A similar result was obtained from the other rivers examined. Figure 4 gives 31 cm as the average order of jamming at the Rantaniemi tide-pole on the first day of ice break-up and 87 cm on the following day which last mentioned value is 17 cm higher than the result obtained from the curve analysis.

"The above mentioned difference method was applied to the observations made in Kemijoki, Kyronjoki and Kokemaenjoki. The average maximum values and the extreme values obtained are given in Table 5. The $\Sigma\Delta_1$ which of the different jamming-covering periods gives the maximum value of the sum was considered as maximum jamming. Maximum jamming occured during or around the phase A_1. If jamming is of long duration and the Δ_1 values are small, difficulties may arise in determining the length of the period. In such cases the method may give too high values.

"Intercomparison of the results of the two methods shows, that the average values differ from each other within the range of from 4 to 17 cm. Use of the difference method implies, as mentioned, that at the higher situated tide-poles no considerable jamming has occured. If the latter distinctly established cases are not taken into account the results for different methods differ less.

"The maximum value of the jamming constitutes from 20 to 60% of the maximal rising of water level during springtime. The results vary considerably for different tide-poles in the same river, depending mainly upon local circumstances."

Wemelsfelder (1954) discusses water level fluctuations due to ice jams as observed in the Netherlands.

"Fig. 3 shows in B an ice sheet of some 35 km of length. Up the river there is a back water curve of 60 km length. The rise of the water above the original level is 3.10 m, i.e. 70% of the depth. From this a reduction of C to 2/3 of the original value can be computed....

"If we take the same roughness of 2/3 and a length of the dam of

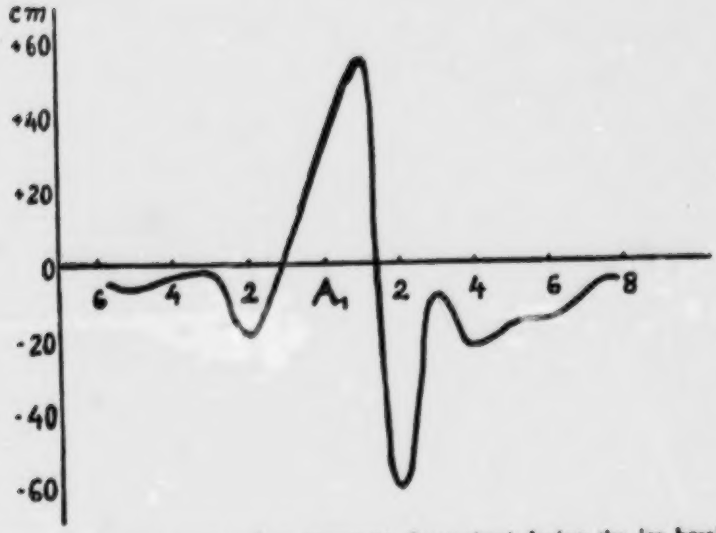

Figure 4. Average course Δ_1 at Kemijoki, Rantaniemi during the ice break-up

(Simojoki, 1952)

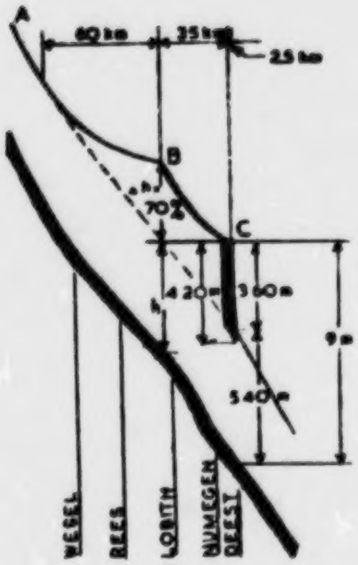
A
60 km
35 km
2.5 km
B
h
70%
C
4.20 m
3.60 m
9 m
h
5.40 m
WESEL
REES
LOBITH
NIJMEGEN
DEEST

Fig. 3
Ice dam on the Rhine near Deest, 1940.
A = open river;
B = ice sheet;
C = ice jam.

(Wemelsfelder, 1954)

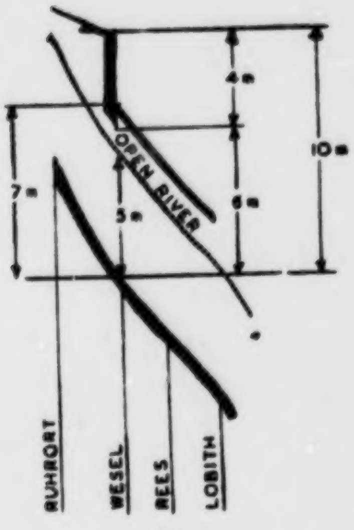
4 m
10 m
7 m
5 m
6 m
OPEN RIVER
RUHRORT
WESEL
REES
LOBITH

Fig. 6
Ice dam near Wesel, 1947. Mean thickness 4 m.

(Wemelsfelder, 1954)

2.5 km, it can be computed that

$$\left(\frac{h_{dam}}{h_1}\right)^{1\,2/3} \text{ must be } 2\,2/3 \cdot 3/2 \sqrt{\frac{2.5\text{km}}{3.60} \cdot \frac{0.40}{2.5\text{km}}} = 0.8$$

so $h_{dam} = 0.9\,h_1$

"In this location $h_1 = 5.40$ m and so h_d must be 4.80 m. That is: the cross section is reduced to 90% of that when the river is open. It is important to remark here that even in a case like this, a closing of the river is altogether out of the question. The original cross-section is almost fully maintained.

"The average thickness of the ice cover is meanwhile in this case

$$9.00 - 4.80 = 4.20 \text{ m}$$

so 10 to 20 times the thickness of an ice sheet."

"It is impossible to define a limit above which the level of the river cannot be dammed up. Higher levels than have been observed seem to be possible.

"This is shown in fig. 6 representing the ice dam near Wesel in 1947, some 50 km upstream the Netherlands-German frontier. The discharge without ice would have given 5 m depth. The total elevation is 5 m.

"The length of the ice dam is supposed to be 2 km. The normal fall on this stretch is 0.22 m, but the ice dam caused a fall of 3 m. From this results, with $C_2/C_1 = 1/3$

$$\left(\frac{h_3}{h_1}\right)^{1\,2/3} = 2\,2/3\,\frac{C_1}{C_2}\sqrt{\frac{I_1}{I_3}} = 2\,2/3 \cdot 3\sqrt{\frac{0.22}{3.00}} = 1.3$$

$$h_3 = 1.2 \qquad h_1 = 6 \text{ m."}$$

According to Berg and Platunov (1936) autumn ice jams on the Neva River have caused water levels to rise as much as 1.35 meters. Spring ice jams raise the level above winter norms.

Chizhov (1956, 1955) developed formulas for forecasting water levels on the Amu Darya River based on data over an 18 year period. Equations are given for both autumn and spring flood levels.

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Ice Jam Effects

Effect on water levels

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Effect on river bed

The erosion and sedimentation effects in Scandinavian Rivers composed primarily of frazil are described by Melin (1954).

"In places where barrages appear, the ice will often fill up a great part of the section right down to the bottom. Therefore the water is forced to follow one or a few channels, flowing more rapidly than before, resulting in a great tendency of erosion.

"Areas where such erosion is common are the upper part of the calmwaters. Here big masses of soil and gravel have been deposited after being brought from the rapids above, and the bottom constitutes a very good ground for erosion when the velocity of the water increases. Sometimes the flow will follow a channel along the riverside eroding it and causing big masses of sediment to plunge into the river....

"Section in fig. 1 shows such a condition with frazil beneath the ice cover where the velocity would be insignificant in summer time.

"The velocity has not often been measured at ice dams but many observations have been made of the storing up of the water level in connection with ice-dams....

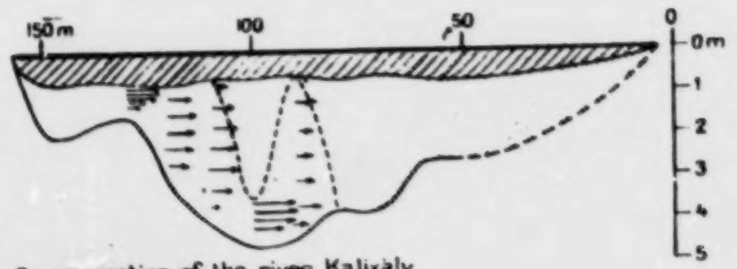
Increase of the water level because of ice-dams downstream in cm

	Nov.	Dec.	Jan.	Febr.	March	April
Mean	3	39	219	268	290	100
Max	60	163	404	471	442	258

"It is evident that the ice masses raising the water level to such a degree must ease the velocity causing considerable erosion in the river valley.

"Because of extensive lake regulations completed in recent years the winter flow has increased up to four times in many rivers. Hereby and because of daily and other short time regulations the way in which the ice is formed and broken down has changed and there has in many places been a tendency towards larger ice dams....

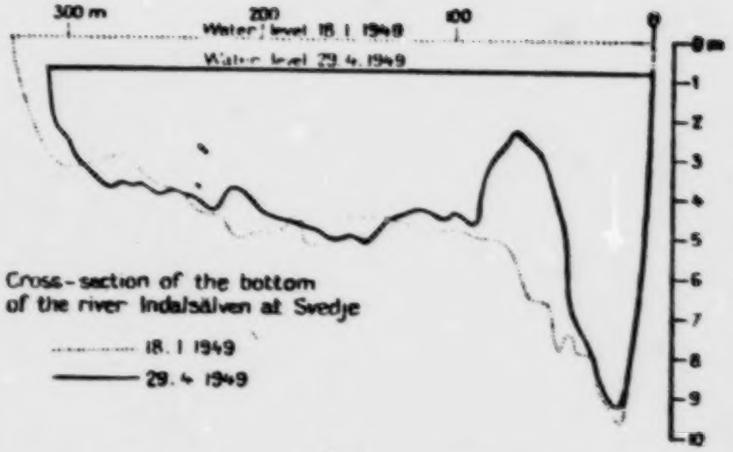
"... Observations are made by measuring the depths occasionally in sharply defined sections, specially where ice dams have been destroyed and the ice masses moved downstream. An example of the effect in the river Indalsalven is illustrated in Fig. 2 showing a profile of the bottom early in the winter 1949, on Jan. 18th, and late on April 4th.


150 m
100
50
0
0 m
1
2
3
4
5

Cross-section of the river Kalixälv at Rödupp 24. 1. 1921

▨ Ice cove — Frazil → Velocity / m/s

Fig. 1

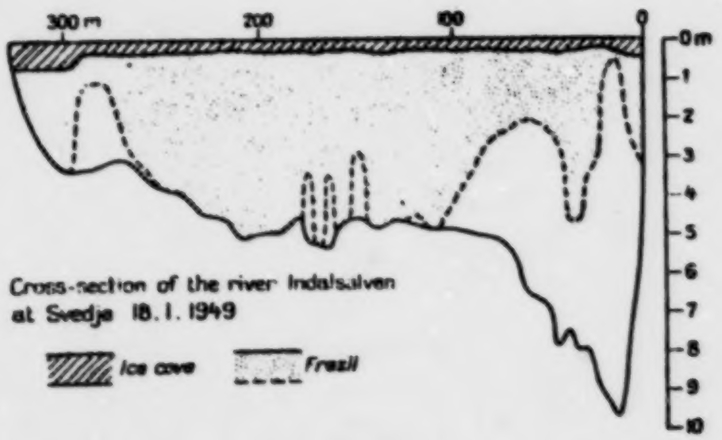

300 m
200
100
0
Water level 18. 1. 1949
Water level 29. 4. 1949
0 m
1
2
3
4
5
6
7
8
9
10

Cross-section of the bottom of the river Indalsälven at Svedje

.... 18. 1. 1949

—— 29. 4. 1949

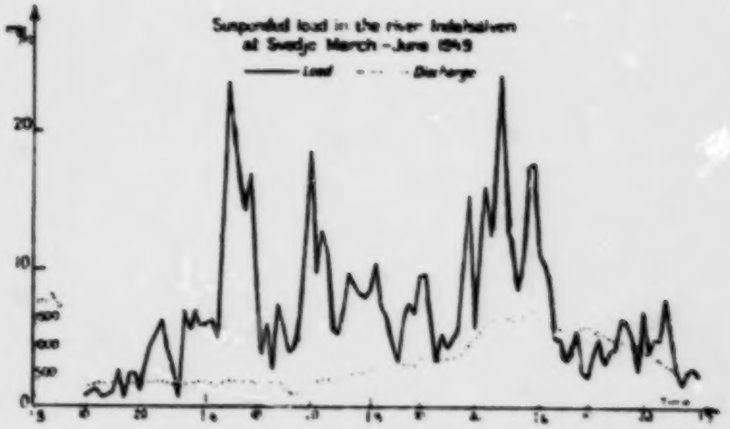
Fig. 2


300 m
200
100
0
0 m
1
2
3
4
5
6
7
8
9
10

Cross-section of the river Indalsalven at Svedje 18. 1. 1949

▨ Ice cove — Frazil

Fig. 3



Suspended load in the river Indalsälven at Svedje March - June 1949

Fig. 4

(Melin, 1954)

No velocity measurements were made but it is evident that the considerable sedimentation that took place in this section between those dates, was due to a decreasing velocity when the ice dam disappeared. Fig. 3 shows the cross-section of the river on Jan. 18th with frazil beneath the ice cover which constitute the ice dam.

"The transportation of sediment in the river in the beginning of April is also illustrated by Fig. 4 showing the suspended load as well as the flow for the period March-June, 1949.... There is a very marked peak of the load in connection with the flood, but an equal one at the beginning of April before the flood, when the ice gathered in the barrage comes off."

Laszloffy (1948) describes river flows under an ice cover pertinent to Melin's (1954) investigation.

"Because of the freezing of the river, the area of the flow section likewise decreases to a considerable degree. Figure 6, in its representation of results of gauging conducted on the Danube, gives some idea of this."

Ice jams on the Danube which constricted the water flow and extensively scoured the river bed are described by Karolyi (1963).

In Wentworth (1932) the processes of erosion, abrasion, transportation and deposition incident to ice jams are discussed.

"Striated cobbles and outcrops were ... observed by Lopatin (1871) in regions not at present subject to ice jam work and were interpreted as being due to former wider extension of the process...."

"The most complete statement in English of the geologic work of river ice found by the present writer is that by Russell (1890).... Immense quantities of ice are carried by flood or forced by dams onto the bank along the river. As results of this action, Russell cites the smoothing and polishing of rocky banks and particularly the upstream sides of bold promontories. Transporting of large boulders, forcing of boulders downstream and outward to elevations on the banks somewhat higher than high water, the scarring and abrasion of trees above high water mark, and the furrowing of sand bars were all mentioned.

"He also noted many curious forms of graved accumulations due to ice movement and ice stranding. Boulder pavements and abraded and striated stones were described and the statement made that were these found in a glaciated region, the most acute observer would attribute their markings to glacial action. However, he concluded in general that 'the scratches on the smooth faces are less regular and less firmly drawn than the groove and striations on typical glaciated pebbles.' Russell believed that boulder clay, closely similar to that of glacial origin, might be formed by deposition from river ice but did not cite any positive example.

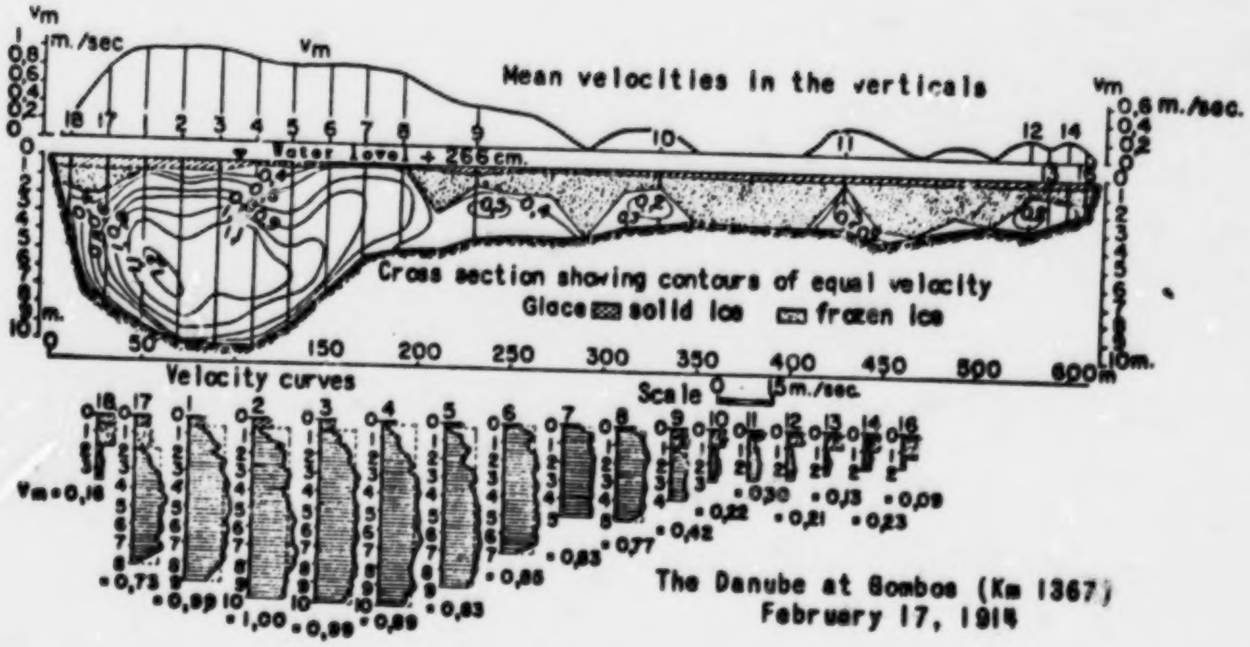


Figure 6. Influence of ice on the flow of water. (Results of gauging by the Hungarian Hydrographic Service). Water level: +266 cm; area of the wetted section: F = 1824 sq m (m^2); mean velocity: 0.75 m/sec; actual discharge: Q' = 1360 cu m/sec; apparent discharge (at the same water level without ice): Q = 2120 cu m/sec; (ratio $\varphi = \frac{Q'}{Q} = 0.64$).

(Laszloffy, 1948)

Compact, lenticular masses of gravel enclosed in fine material exposed in caving river banks were thought possibly to be ice-transported.

"Kindle (1918) has observed pavements in the channel of the Mackenzie River composed of cobbles and boulders which have their upper surfaces planed and striated. He noted abundant evidence of the gouging and plowing action of river ice and mentions several rock basins in limestone which were thought to have been formed by plucking.... He noted the concave, cobble-paved profile of the banks.... That striations on cobbles and boulders can be produced by moving river ... ice was pointed out by Leffingwell, (1919)....

"... These pavements and features produced by intense abrasion by river ice have also been described by Tolmachoff (1928). He mentions specifically the production of rounded rock masses marked by scratches and grooves which are similar to the roches moutonnees...."

"... All agree that no bank materials except solid rock ledges and cliffs are capable of withstanding the main thrust of the ice. Gravel banks are invaded, carved away, or caused to collapse on the ice. Trees are overturned or broken off, and lesser vegetation is uprooted or overridden and stripped of bark and foliage. Straight-trunked coniferous trees, shoved top foremost, are reported to have been thrust into banks of alluvium and gravel like horizontal piles for distances of thirty or forty feet before being snapped off. These phenomena and many others attest the tremendous power of the ice as exerted for short periods of time. It should be recognized, however, that powerful though the ice is in the aggregate, it is capable of exerting only a definitely limited pressure per unit area. This is fixed by the crushing strength of ice....

"... Ice tends to move straight forward at a point where the channel curves and thus to bear strongly against the outer bank.... At the heads of low islands the ice mass tends at first to override the low land, later to divide, and to develop between the two ice trains a tumbled and twisted pile of stranded ice blocks...."

"Boulder Pavements.--These are the most general and characteristic products of ice work along the part of the Yukon River examined. They consist of comparatively smooth surfaces made up in part of subrounded cobbles and boulders, embedded in a matrix of fine sand and silt, with their upper surfaces nearly flush with the surface of the pavement. The upper and landward margin of the boulder pavement is commonly at the level of ordinary high water, but well below flood stage, and the surface slopes toward the channel at angles of 12 or 15 degrees at first, the slope decreasing rapidly and becoming quite gentle at the level of low water....

"The boulders in the pavement more commonly show an upper surface which slopes slightly upstream rather than one which slopes downstream, thus suggesting a tendency to become firmly lodged only when they are originally flat or slightly imbricated....

"The boulder pavements occur along the shores both of the mainland and of islands. They are found on bars adjacent to the banks and to islands....

"... At numerous places gravelly pavements of somewhat incoherent material had been developed by the ice run of the previous spring, but in midsummer were in process of destruction by waves and currents, which gradually wash out the matrix at the water line and reshape the coarser debris into incipient beaches....

"Planed and Furrowed Bars.--In general these surfaces differ from boulder pavements in that the rock fragments are smaller and more uniform in size, being the normal washed gravel of the stream, and in that there are few, if any, individual large fragments firmly embedded in a matrix of finer material. The planed and furrowed bars are therefore surfaces of much less stability than the boulder pavements and probably do not survive with any great constancy from one season to the next, though it is quite likely that they would be redeveloped in successive seasons on the same bar.

"Three elements are present on these bar surfaces: planed surfaces, grooves, and ridges. In places these bars consist of a planed surface over which the pebbles are somewhat firmly pressed down to a common level. Below this level a few narrow grooves are commonly cut. At the margins of the planed surface linear ridges of excess gravel are commonly found. In other places the surface was made up in more nearly equal parts of gravel ridges and somewhat flat-bottomed intervening troughs. The relief of grooves cut below a smooth planed surface is commonly not more than a few inches; that of the gravel ridges above the plane surface may amount to a foot or two and occasionally more.

"The largest areas observed over which such planing and grooving were developed were perhaps five to ten acres in extent. They were mostly bars situated well out in the channel, or at the heads of islands and subject to progressive exposure with the falling water stages of late summer....

"On large parts of the planed and grooved bars, the markings are practically straight and parallel. In some places, however, especially at the parting point near the head of an island which was not over ridden by the ice, the grooves and ridges are irregular and confused. Various directions of ice movement are shown, and occasionally the grooves are curved, or show abrupt changes of direction at certain points.

"Aligned Striae.--Apart from the presence of bruises and striations on the river cobbles, it is noteworthy that where boulders and cobbles are imbedded in a boulder pavement, the striations and other markings on all the rock fragments show a distinct, alignment parallel to the bank, or directed slightly inshore and downstream. In some instances

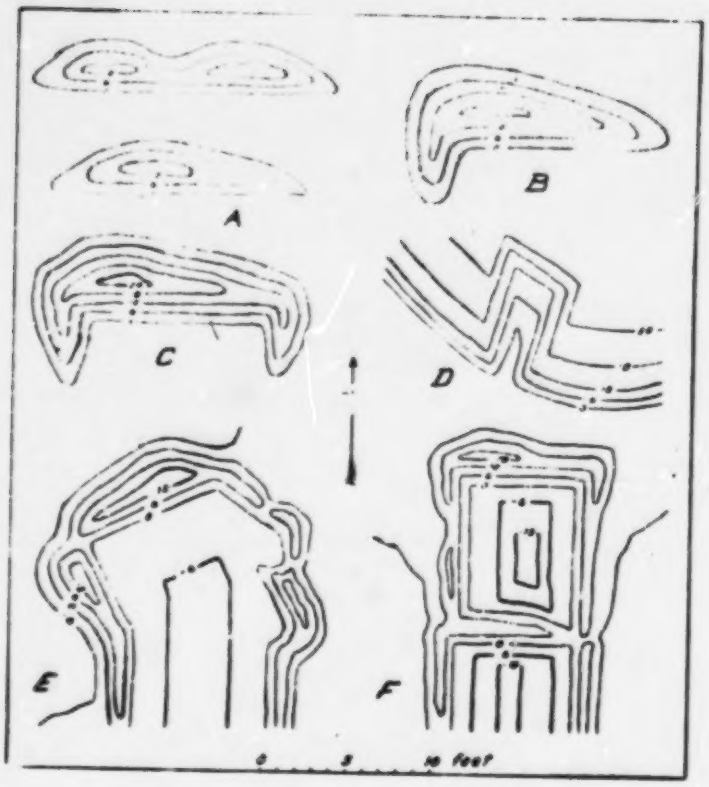


Fig. 6 Contour maps of minor ice-push features, contour interval 6 inches. (A) Two simple, transverse excess gravel heaps. (B) A transverse heap with a single longitudinal appendage. (C) The same with two appendages, forming the "square crescent" type. (D) A furrow of the type which forms a furrow bay at the appropriate water stage. (E) Excess gravel heaps of the form developed when a rectangular ice block is thrust forward and then slightly twisted before being abandoned by the thrust. (F) A furrow with adjacent excess gravel heaps, and closed by the frontal excess heap formed by a subsequent thrust. (Wentworth, 1932)

two sets of markings on a given boulder appear to have been formed with the boulder in the same position and to represent different directions of movement in different seasons....

"Over-ridden and Aligned Vegetation.--In some places where low banks are favorably situated with reference to the configuration of the river channel, ice commonly overrides these banks without scouring them intensely enough to entirely destroy the vegetation....

"Furrow Lakes and Bays.--Erosional and depositional patterns of slight relief, such as those due to ice push, are especially clear when the component parts are partly in water and partly out of water. One of the common features which is thus apparent is a small, parallel-sided bay where water enters a sloping trough cut by the shoving of an ice block onto the head of a bar or island, or diagonally on shore. Such bays are very small, naturally, and range from a foot, or less, to 10 or 15 feet in width, and from similar lengths to those two or three times as long. Not uncommonly such bays are square ended, or if the bottom is slightly tilted to the side, the end may be straight but oblique to the sides....

"Transverse Bays.--These differ from the furrow bays previously described in that they are formed along a shore where several transverse ice-push gravel heaps extend offshore and into the river on a sloping, planed, gravel surface....

"Excess Gravel Ridges.--Two sorts of short, compact, gravel accumulations are found, besides the long ridges which are strewn on the bars parallel to the ice movement. Those here described as excess gravel ridges are due to the pushing along of masses of roundstones in front of the ice, or mingled with ice blocks. After the ice melts, the gravel slumps slightly but retains various rectilinear outlines which indicate the origin of the ridges. Commonest of these is a simple cross ridge lying on a cobble pavement or across one or more flat-bottomed furrows....

"Another very common type shows a transverse ridge joined to a single, short linear ridge, the two forming a right angle with a straight lined inner margin and a somewhat rounded outer margin. A still more complicated form consists of a transverse ridge with two such linear appendages, forming a square 'crescent.' These heaps commonly range from a few inches to two or three feet in height. In many instances they are intermingled in somewhat confused fashion owing to successive thrusts of the ice....

"Cobble Cones.-- ... are essentially the result of the cascading of small masses of gravel down from the tops of ice blocks or between the crevices separating several such blocks. The gravel may reach the tops of ice blocks by falling from undermined banks or by the active and powerful invasion of gravel banks by ice push...."

"Ice Pushed Boulders and Uprooted Trees.--Occasionally as one travels down the Yukon River he sees large isolated boulders and blocks of rock foreign to the district, which are pushed high on the river banks...."

"Rounded and Striated Surfaces.--A careful search was made for well-marked instances of ice erosion of rocky islands and projecting ledges, producing forms simulating roche montonnees. These were not abundant and many showed only a feeble and obscure development. However, several such islands and ledges were clearly smoothed and rounded in such a way that one could easily distinguish the stoss and lee slopes, and definite evidences of plucking were seen adjacent to the joints....

"Abrasional Work on Boulders and Cobbles.--Abraded cobbles are of great importance in that they are susceptible of long preservation after physiographic forms have been destroyed and after much of the material has been transported to new sites.... Stones showing striated surfaces varying from an inch or two in diameter to four or five feet in diameter were found. In shape they vary from angular to well rounded, the forms being indistinguishable in the main from other river cobbles, which were not striated....

"Three chief kinds of surface markings were noted on rock fragments and roundstones. These may be called striations, bruises, and rub marks.... Striations are ideally narrow, straight, or nearly straight, scratches cut cleanly below the surface on which they appear and not in any way dependent on alteration of the surface adjacent to them. They may be isolated or so closely spaced as to practically form the surface with their merged flutings. Bruises are cruder markings than striations, are commonly shorter and broader than the latter, and in many instances are developed in parallel groups, or staggered in a diagonal or en echelon pattern. However, they differ essentially in being due largely to crushing or hard rubbing of the surface rather than to clean graving of the material. Not uncommonly they are made more conspicuous by a fracturing and shattering of the surface adjacent to them, so as to produce a definite color difference, whereas the striations are ideally distinguished by relief only.

"Rub marks are visible as a result of the crushing of the surface of softer roundstones, or by the rubbing off of the material of other cobbles which have passed over them. Such marks may in part be removable by washing or by vigorous scrubbing.... It may be stated in general, however, that numerically the larger number of roundstones are characterized by bruises, rub marks, or short random, and often somewhat curved, striations. But strongly parallel striation patterns are by no means lacking, and surfaces showing two or three superposed parallel patterns are not difficult to find.

"The proportion of cobbles in certain situations which show some degree of scratching is high, probably in many places includes a majority of all those above certain sizes, and is equal to, if not superior to,

> the proportion shown in the most favorable deposits of glacial boulders. Many of the larger boulders are almost covered with scratches, certain flatter faces being characterized by strongly systematic patterns, and the remainder of the surface showing numerous shorter, random and curved striations and bruises. The number and character of scratches on the roundstones appear to be definitely related to the site in which they are found...."

Williams (1953) also describes the erosional effects of ice on the Yukon River based on one seasons observation. His observations seem to agree well with Wentworths' (1932).

Sedimentation effects caused by ice jams in the Yukon River are described by Eardley (1938).

> "There remains still another process of river deposition to be described; namely, that of ice-jam flood sedimentation. This is the only known means of accounting satisfactorily for the height to which some bar and inside meander-bend deposits are built...."

> "A flood at Koyukuk about ten years ago rose well over a 20-foot bank on which the village is located and deposited a thin layer of silt wherever the water had been."

Eardley quotes Chapman (1931):

> "These floods appear to be local, and to be caused by ice jamming.... The water remains at the high level stage only a day or two and then goes down, leaving everything covered with a layer of mud.
>
> "... Inquiry about the 'mud' or 'deposits' laid down during the high water was made at every opportunity. The answer was invariably a thin layer of slippery mud, maybe one-half inch, maybe 2 inches thick...."
>
> "An observation on the cut-bank opposite Holy Cross furnishes a good example of local flood deposition at a rather fast rate. The section ... shows the upper 9 feet of the bank material to be made up of three distinct layers. At the base of each layer is a jumbled layer of drift-wood. Large stumps are particularly common. All the wood bears unmistakable evidence of river drift over a long distance. Above each layer of drift-wood is gray loam (chiefly silt, some very fine sand, some clay), the common river deposit in all the present-forming bars...."

Rodevich (1936) comments on some processes which occur in the Yenisey River which are similar to those observed in the Yukon.

> "... The floating masses of ice, when they encounter sections of the river which have not yet opened up, pile up and some of the ice is pushed out onto the banks, grinding the rocks, destroying the bluffs and leaving accumulations of rocks along the banks. Because of the power of the ice

> and grandiose scale of the ice drift, the action of the ice on the banks is considerable. Thus, for example, at the Brekhovskiy Islands at the mouth section of the Yenisey River, the ice comes to 200 meters from the shore, cutting down the willows. When the ice melts accumulations of sand, pebbles, large and small boulders remain on the banks....
>
> "Ice activity on river banks is particularly heavy in the northern part of the Kray on such large rivers as the Yenisey, the Khatanga, and others.... As movement proceeds downstream the ice floating on the surface encounters, en route masses of ice on sections of the rivers which have not yet opened up, and the floating ice piles up in great quantities at such points. At the same time, this results in considerable activity on the banks, destroying bluffs, grinding rocks and large, individual, boulders, cutting into the soft soils along the banks, and depositing accumulations of rocks on the banks."

Kindle (1920), in describing ice jam characteristics in the Mackenzie River Basin states:

> "... There is scarcely a mile of the river banks that does not show traces of the destructive work done by these great blocks as they travel seaward. In some places the spruce trees at the top of the banks have been snapped off like straws; in others the clay banks have the appearance of having been plowed by titanic plows. In late summer the gravel bars about the mouths of tributary streams often show numerous grooves cut by the shoving of grounded ice blocks."

Effect on river bed

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Forecasting

Forecasting ice jam formation

Shulyakovskii (1963) describes a system for forecasting spring ice jams based on water stage during the freeze up period.

"Forecasting ice jamming

"The principal conditions for ice jamming are ... (1) the preservation of the ice cover downstream on the part of the river on which ice breakup occurred and ice drift began and (2) sufficient steepness and velocity of the flood wave. The first condition to some extent depends on the second.

"As a characteristic of the second condition the rate of rise of the water stage before the beginning of ice breakup is usually taken. On some rivers the second condition exists every year or almost every year, in accordance with the climatic and orographic conditions of the given river basin. Such, for example, are the large rivers of Siberia, which flow from south to north, where ice breakup is caused mainly by snowmelt floods forming in the upper (southern) parts of the basins. In this case, in order to forecast the possibility of an ice jamming it is sufficient to know whether the first condition (preservation of the ice cover, absence of conditions for breakup at the time of the approach of the flood wave) is satisfied on the particular river stretch. The first condition is fulfilled every year when the river slope and the flow velocities over a long stretch decrease generally. This is particularly true in the case of successive decrease in the slope. Therefore, ice jams always form there during spring breakup on the river, and it is not necessary to forecast the probability of an ice jam. Such a stretch, for example is the stretch of the Toma River downstream from the town of Tomsk.

"If, however, there is no general decrease in the slope over a large stretch of a given river, and ice jams form in places where the flow velocities decrease when the stream passes from a shallow stretch to a deep pool, or where the river bed is constrained, or where there are islands, then the first condition (preservation of the ice cover) is not always fulfilled and ice jams do not form every year. This is connected with the ice-cover characteristics and their distribution along the river.

"As yet there are no sufficiently accurate methods of forecasting ice jamming which take into account direct characteristics of the ice cover on the given river stretch (thickness, strength of cohesion to the shores or to the shore ice, depth of the snow cover on the ice, roughness of the under surface). Field investigations necessary for this are very laborious, and data of a fairly long series of preceding years and for each current year are necessary in the preparation of a forecast.

"Ice jams during breakup form, as a rule, when freezing takes place with considerable ice gorges. A forecast of a considerable ice jamming may, therefore, be prepared from the relationship with one or another ice-jam characteristic. The rise $\Delta H_{\text{н}}$ in the stage during the formation of the ice cover can be taken as a characteristic of ice jamming. On rivers where the long-time amplitude of the water-stage fluctuation before the beginning of ice formation is negligible, the maximum water stage $H_{\text{н}}$ during the initial stable ice period may be taken....

"The Yenisei stretch not far downstream of the town of Krasnoyarsk along 19 km is a series of shallows (Ladeinye shallows) with islands. Farther downstream, between the villages of Berezovskoe (19 km downstream of the town) and Kubekovo (35 km still farther down) a deep pool is found. During formation of the ice cover, the advance of the ice edge toward the town is connected with a rise in the water stage, wich (sic) continues for some time after the formation of stable ice within the town boundaries. At the time of the formation of the ice cover, ice pushes are observed fairly frequently.

"Two centers of ice jamming at the time of ice breakup of the river are observed here. The first center is near the islands on Ladeinye shallows. However, strong ice jams do not form there: as a rule, the break-through of the ice jam continues until all the ice from upstream approaches the jam. The second, main ice-jam center is a deep pool downstream from the village of Berezovskoe. An ice jam usually forms in the upper part of the stretch, on the transition from a shallow to a pool, i.e., on an abrupt change in the river slope. There ice drift encounters a stable-ice stretch with a thick and strong ice cover and a strong ice jam forms. In individual cases ice jams are also formed in other places. Figure 102 gives a clear idea of the probability of ice jamming for different water stages $H_{\text{н}}$ at the beginning of the stable ice period. The shaded columns in the graph correspond to cases of ice jamming of the ensuing spring. From the figure we see that for $H_{\text{н}}$ (according to the Krasnoyarsk water gage) at a water stage below 240 cm an ice jam formed only in one case out of 31. For $H_{\text{н}}$ for stages from 240 to 280 cm ice jams formed in half the cases. For $H_{\text{н}}$ with a stage above 280 cm ice jams formed in 88% of the cases. For $H_{\text{н}}$ above 310 cm ice jams formed in 7 cases...."

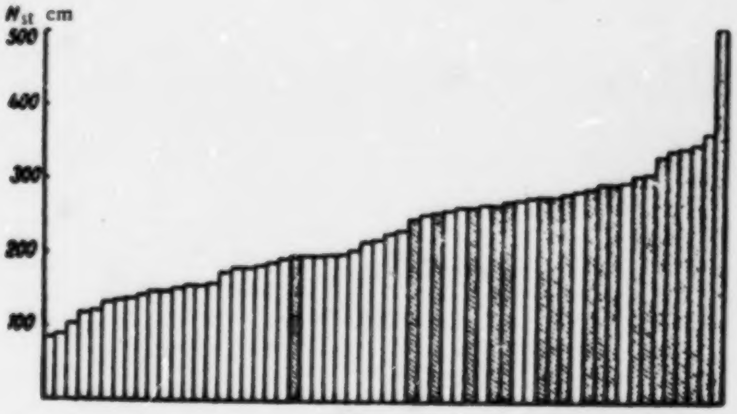

FIGURE 102. Relationship between the formation of an ice jam on the Yenisei River downstream the town of Krasnoyarsk and the maximum water stage in the initial stable-ice period (H_{st} in cm above the datum line of the graph of the Krasnoyarsk water gage).

(Shulyakovskii, 1963)

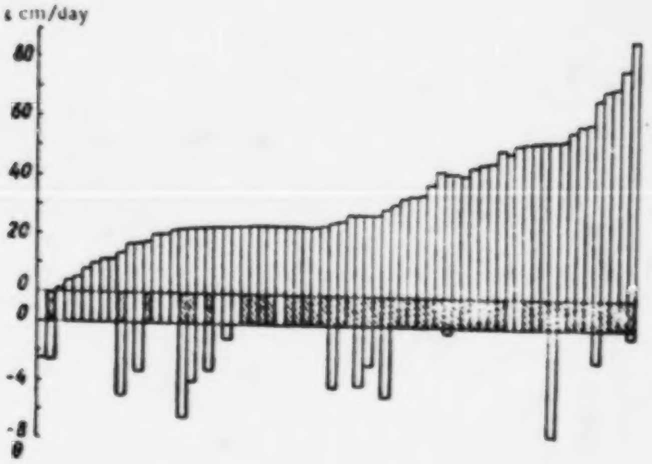

FIGURE 103. Ice jamming on the Neman River downstream from Kaunas (before the construction of the Kaunas hydroelectric plant) as a function of the rate i of the water-stage rise until the ice push at Kaunas and of the negative air temperature θ_- at the time of the ice breakup.

(Shulyakovskii, 1963)

"It should be noted, however, that although ice jams form, as a rule, on a definite stretch of the river, their formation in other places also is not excluded. In particular, if ice jamming occurs downstream of the town Krasnoyarsk, then the probability of ice jamming downstream of the town of (sic) decreases, since at the moment of the break through of upper ice jam the ice cover on the lower stretch has already had time to disintegrate. For a more reliable forecast of the probability of ice jamming, it is necessary to have observations not for a single isolated gaging site, but for a series of closely-situated sites on the stretch above and below the main site. In important cases the probable places of ice jams can be determined from ice courses at the end of winter....

"On other rivers, in particular on rivers of the west of the ETS, the principal index of the possibility of the formation of an ice jam is the rate of the water-stage rise before ice breakup. A certain dependence of the probability of ice-jam water-stage rise on the negative air temperature at the time of ice breakup is also observed. Figure 103 shows the relationship between the probability of ice jamming on the Neman River downstream from Kaunas (before the construction of the Kaunas hydroelectric plant) and the rate of the water-stage rise and the negative air temperature.

"In this figure, for each case of ice breakup the mean rate of stage rise (in cm/day) at the water gage of Kaunas, during the period from the day of a rise at a rate of not less than 10 cm/day to the day preceding the first ice push, is plotted above the abscissa and the mean-diurnal negative air temperature, the lowest of those observed in the breakup day or in the next day, is plotted below it. The shaded areas denote cases when at the time of the breakup an ice-jam stage rise was observed.

"It follows from Figure 103 that if the air temperature at the time of ice breakup is positive, ice jams form when the mean rate of the water-stage rise is not lower than 24 cm/day. If the air temperature drops at the time of breakup below -25°, ice-jam stage rises are observed at the Kaunas water gage also for lower rates of stage rise.

"The probability of ice jamming for a mean rate of stage rise not less than 24 cm/day is 93%. The total confidence limit of the method of forecasting ice jamming, taking into account the rate of stage rise and the air temperature at the time of ice breakup, is 93%.

"The rate of stage rise can be determined from actual data with a mean forewarning period of 2-3 days.

"To forecast ice jamming in the case of a rate of stage rise of less than 24 cm/day the air temperature forecast is necessary.

"The method of forecasting ice jamming from the rate of stage rise before ice breakup and from the air temperature of the first breakup days, originally developed for the Neman River in the region of the town of Kaunas, also gave good results for rivers of the west and north of the ETS.

"Forecasting of ice jamming from spring characteristics - rate of stage rise and air temperature - does not exclude, in principle, the possibility of forecasting the probability of ice jamming from autumn characteristics - the rise of stage at the beginning of the stable ice period, autumn ice pushes, etc.

"The forewarning period of forecasting on the basis of the rate of stage rise can be increased by analyzing (from observation data) the dependence of the rate of stage rise on its determining factors."

In conjunction with the fall ice jamming, Popov (1957) develops a system for the stoppage of ice flow.

"In analogy with the method of forecasting the appearance of ice, the development of a method for forecasting the stoppage in the flow of ice in a given sector of a river consists of determining the minimum sum of negative degree-days of air temperature, needed for the stoppage in connection with the water volume of the river, and the critical air temperature at which the phenomenon takes place. Practically, the procedure is reduced to the plotting of a graph showing the relationship between the sum of frost degree-days during the time from the day the drift ice (grease ice) appears to the day the flow of ice stops and the indicator for water volume of the river --- the discharge or water level in the river when the grease ice appears. An example of such a dependence for a sector of River Dnepr from Kiyev to Kremenchug is presented in fig. 141.

"... For forecasting the time when the flow of ice stops it is not sufficient to know only the needed sum of frost degree-days. Experience demonstrates that with the accumulation of such a sum, the flow of ice stops only if the subsequent mean daily air temperature is lower than a certain critical value. This critical value of temperature depends also upon the water volume of a given river, i.e. upon the discharge or level of water in it....

"In order to determine the critical air temperature t_{cr}, supplementary empirical relationships are found ---namely:

$$t_{cr} = f(H_{d.\ ice}) \text{ or } t_{cr} = f(H_{i.\ ice}),$$

in which $H_{d.\ ice}$ denotes the water level in river in the day when drift ice appears, $H_{i.\ ice}$ denotes the water level in the day when immobile ice formed.

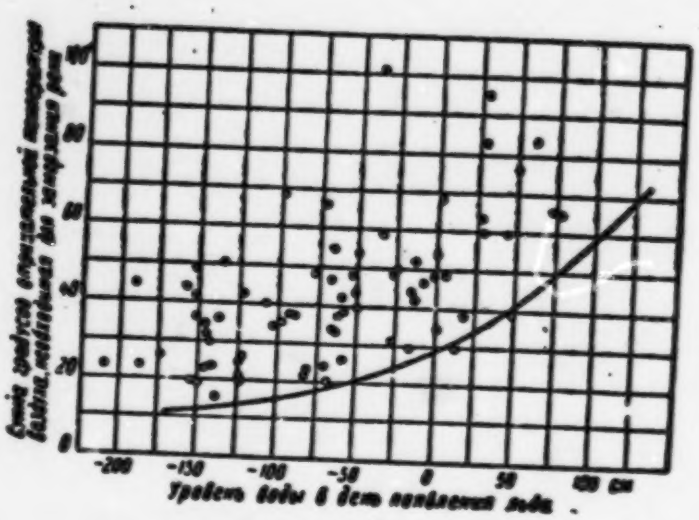

Fig. 141. Computational graph for the determination of the minimum sum of frost degree-days which is needed for the formation of immobile ice in a sector of River Dnepr from the City of Kiyev to the City of Kremenchug. (Popov, 1957)

Key.

Horizontal line: water level in the day when the ice appears.

Vertical line: the sum of negative degree-days of air temperature needed for the freezing of river.

"The water level prior to the stoppage in the flow of ice characterizes better the transporting ability of a river than the water level in the day when the ice appears, because during the ice jamming the water level in the river can change substantially. However, for the preparation of forecasting, the water level must be known in advance. Therefore in practice, the critical temperature of stoppage in the flow of ice is more frequently determined in relationship with the water level in a river on the day the ice appears, which is always known at the moment the forecast is issued. The plotting of computational graphs for determining the critical temperature is carried out by two methods.

"The first method is based on observational data obtained in the preceding years, from which the values of water level in a river on the day when the grease ice had been formed are taken, i.e. the same values, which are utilized for the plotting of computational relationships for the determination of minimum sum of frost degree-days needed for the stoppage in the flow of ice. Further, from each day of the period, beginning from the time when the needed sum of degree-days has accumulated to the time when the flow of ice has stopped, inclusively, are taken the mean daily values of air temperature recorded each year at the same station, the data which have been used for the determination of the minimum sum of frost degree-days. For the plotting of computational relationship, the corresponding values of water level and air temperature are laid off on the graph. Further, all the points pertaining to the days when the immobile ice did not exist yet are marked with one symbol, whereas all the points pertaining to the stoppage in the flow of ice are marked with another symbol. According to the position of the last point, the lower envelope is drawn. This curve is used for the determination of the critical air temperature, at which immobile ice is formed in the given river sector. An example of such a graph is presented in fig. 142.

"The second simplified method of plotting the computational graph $t_{cr} = f\ (H_{d.\ ice})$ differs from the first one, in that its plotting is based only on the values of air temperature at which the immobile ice is formed. In other words, only those cases which relate to the formation of immobile ice (solid dots in fig. 142) are laid on the graph. This method is less accurate. The lay off of two fields of dots, as it is done in the first example, makes it possible to draw a more dependable curve of critical temperature."

Spring ice jams are also analyzed.

"Forecasting of the time of ice breakup in rivers, even with a rough probability, are of substantial significance. On the basis of the forecasts, the measures in fighting the ice jams and protecting the structures during the ice debacle are planned and steps are taken to insure safety in case of development of large-scale ice jams and inundation.

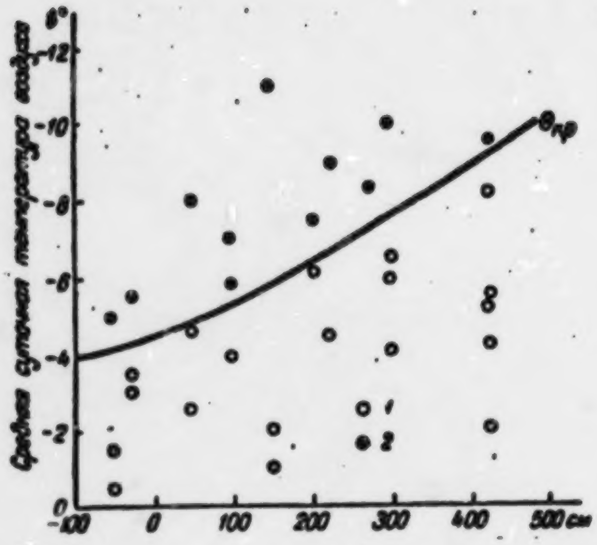

Fig. 142. Computational graph for the determination of critical air temperature in accordance with the water level in the river. (Popov, 1957)

1--the air temperature above the critical point (the immobile ice has not been formed); 2--the air temperature below the critical point (the immobile ice has been formed).

Key.

Horizontal line: water level on the day when the ice appears.

Vertical line: the mean daily air temperature.

"It follows from the examination of the main factors of ice breakup in rivers that the time of ice breakup must in the final analysis depend each year upon the time when the air temperature passes the 0°C point, upon the thickness of ice cover, upon water reserves in snow cover and upon the intensity of heat influx."

"The final transition of air temperature across the freezing point is considered to have occurred when the return of cold is either not observed at all, or the cold is so weak and brief that it cannot substantially affect the further development of spring processes. As a criterion of temporary cooling can be considered its duration and the sum of negative degrees of the mean daily air temperature. If prior to a brief return of cooling lasting from 1 to 3 days a considerable sum of positive degree-days of air temperature has accumulated and the development of spring processes has begun, and if the sum of negative degrees of air temperature during the cooling interval makes up a considerably smaller value, then such a return of cold is not taken into consideration when the final date of temperature transition across the zero point is determined."

"In certain instances ... the sum of positive temperature degree-days calculated on the basis of its observation at a given time appears to be more representative with respect to heat influx. Most frequently the use of such an indicator is necessary in southern areas, where a substantial melting of snow and ice is not infrequently the result of melting during the warm up in the day when the mean daily air temperature is close to the freezing point or even negative.

"As demonstrated by investigational tests, the thickness and firmness of ice in rivers is satisfactorily characterized by such indirect indicators as the sum of negative degrees of the mean daily air temperature during the ice period. Such an indicator must be used when working out the methods of forecasting ice breakup in rivers because the usual measurements of ice thickness, which are carried out in a single point at an observation station, are not representative.

"An example of a computational graph for determining the sum of positive degree-days of air temperature is presented in fig. 144. Each of the straight lines on the graph corresponds to a definite sum of frost degree-days during the time from the beginning of a continuous ice cover to the time when the air temperature passes the freezing point in the spring, which, as was pointed out above, characterizes the thickness of ice cover....

"The data on air temperature and ice phenomena in a given river sector for the greatest possible number of years of observations are used as the initial material for the construction of the graphs. On the basis of observations on ice phenomena for each year, the dates marking the beginning of continuous ice cover in rivers, T_{ice}, and the breakup of ice, T_b, are determined for each year.

"On the basis of data on air temperature, the time when it finally passes the freezing point in the spring $T_{0^{\circ}}$, is determined and the sums of frost degree-days during the period from the date marking the beginning of fast ice cover to its breakup ($-\Sigma t$) are calculated. Further, the sums of heat degree-days that have accumulated during the period from the date marking the transition of air temperature across the freezing point to the date of ice breakup, $+\Sigma t$. By utilizing the same data on air temperature, the calendar periods of winter thaws are determined and the sums of heat degree-days for each of the periods, $+\Sigma t_{\text{thaw}}$, are calculated.

"The sought for sums of heat degree-days during the period from the date marking the transition of air temperature across the freezing point to the date marking the breakup, $+\Sigma t$, are added to two variations, including and excluding the temperature of the day marking the breakup of ice. This is necessary for a more correct drawing of the mean lines characterizing the relationships on the computational graphs.

"The computational graph is constructed in two steps. At the beginning the preliminary graph

$$+\Sigma t = f\left[T_{0^{\circ}}, (-\Sigma t)\right]$$

is plotted on the basis of data obtained in years without winter thaws.

"The graph is plotted the usual way, the only difference being that two dots corresponding to the sums of positive degree-days, including and excluding the temperature of the day of ice breakup, are marked for each year (fig. 144). The sums of negative degree-days of air temperature are indicated above each pair of dots, in accordance with which the calculated straight lines are drawn.

"In the final plotting of the computational graphs, the influence of winter thaws is taken into account.... The correction for the thaw is assumed to be proportional to the sum of positive degree-days during the thaw. Hence, the sum of positive degree-days that is necessary for the breakup is expressed by the following formula:

$$+\Sigma t_{\text{calcu.}} = +\Sigma t - k\,(+\Sigma t_{\text{thaw}}), \qquad (167)$$

[corrected. Ed.]

where $+\Sigma t$ denotes the sum of positive degree-days that was needed for the breakup of ice without winter thawing; $+\Sigma t_{\text{thaw}}$ denotes the sum of

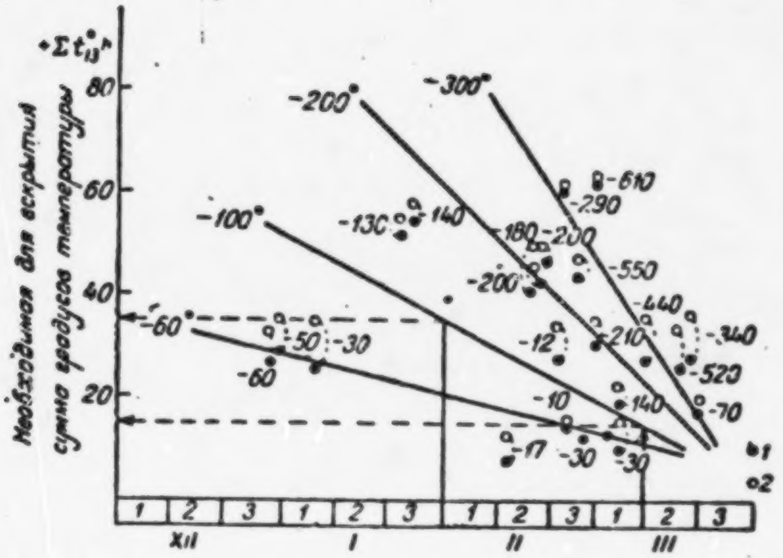

Fig. 144. Computational graph for determining the sum of positive degree-days of air temperature that is needed for the breakup of ice (according to L. G. Shulyakovskiy). (Popcv, 1957)

1 - (solid dots) sum of degree-days excluding the day of ice breakup; 2 - (empty circles) sum of degree-days including the day of breakup.

Key. Vertical lines: the sum of temperature degree-days needed for the breakup of ice.

positive degree-days during the thaw; k denotes the coefficient of proportionality, depending upon the time when the final transition of air temperature has passed the freezing point and upon the time when the thaw had been observed.

"For each thaw, the coefficients of proportionality are determined with the aid of a computational graph, plotted on the basis of data obtained in winters without thaws as the ratio of the sum of positive degree-days, which is needed for the breakup of ice in rivers when no thaw has occurred, to the sum of degree-days which would have been needed if the transition of air temperature across the freezing point had occurred at the time of winter thaw, provided of course that all the other conditions are equal:

$$k = \frac{+\Sigma t}{+\Sigma' t} \,. \qquad (168)$$

"Having determined in this way the corrections for thaws and the computed values for the needed total heat degree-days, the final graph is constructed as a function of

$$+\Sigma t_{\substack{\text{calcu.}\\ \text{[corrected. Ed.]}}} + \Sigma k\,(+\Sigma t_{\text{thaw}}) = f\left[T_{0^{\circ}}\,,\ (-\Sigma t)\right],$$

which is used in forecasting."

" (Where T_0o = date the air temperature finally passes the freezing point in the spring, $-\Sigma t$ = total negative degree-days during winter, and left side = $+\Sigma t$ or sum of positive degree-days needed for breakup if no winter thaw had occurred)." (Ed. remark)

"The total heat degree-days needed for the breakup of ice, if no thaws have occurred, are read off the graph, but in the case of thaws the sum is calculated on the basis of the formula given earlier (167). The breakup time is determined on the basis of the expected variation of air temperature. In this case, the day when the needed sum of heat degree-days has accumulated is considered to the date of ice breakup.

"The problem of forecasting is solved differently for rivers, in which the rise of water level and its intensity are of great significance.... The totals of heat degree-days needed for the breakup of ice in such rivers depend mainly on the intensity of warming and the water reserves in snow cover....

"According to L. G. Shulyakovsky, the total degree-days of positive air temperature needed for the breakup of ice can be approximately determined as a function of two variables -- namely, the mean air temperature during the period from the transition of the temperature across the $0^{\circ}C$ point (t_{mean}) and the number of days from the same transition to the beginning of intense rise of water level in the river (N). The duration of the latter period serves as an indirect characteristic of snow reserves in a river basin and of conditions marking the beginning of its water discharge....

$$+\sum t_{calcu.} = f(t_{mean}, N)."$$

[corrected. Ed.]

"The main deficiency of the methods used at present for short-term forecasting of ice breakup in rivers is their low probability level, which is to a considerable degree determined by the limited possibilities in weather forecasting....

"The regular relationship between the water level of the first movement and the maximum water level during the period of immobile ice is, in all probability, typical not only of the Volga (fig. 145) which can be readily verified for any river during the preceding years by plotting the graphical relation $H_{mov} = f\ (H_{max.\ wint.})$."

Novoselov (1961) describes a system for empirically forecasting autumn ice jams and freeze-up based on meteorological forecasts at a given locality.

"We shall try to review the peculiarities of summer and autumn atmospheric circulation and express them collectively, in order to obtain an objective method of forecasting the freezing-over of rivers.

"A slight change in the average monthly air temperature from August to September reflects the stability of summer types of atmospheric circulation, a later beginning of autumn and, consequently, the later appearance of ice and the establishment of an ice cover. On the other hand, a large change in the average monthly air temperature from August to September indicates an instability in summer types of atmospheric circulation, the active growth of autumn types and, consequently, the earlier appearance of autumn ice phenomena and earlier ice jams. Graphs of pertinent relationships are shown in Figure 1.

"Observing Figure 1, one can establish that, in individual cases, despite great changes in temperature from August to September, autumn icy phenomena began later and freeze-up appeared later than consequently would have been expected....

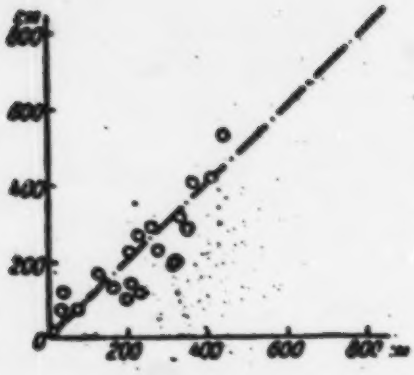

Fig. 145. Relationship between the height of water level in the Volga at the city of Kuibyshev during the first ice movement and the maximum water level during the stoppage in the flow of ice. (Popov, 1957)

Key.

Horizontal lines: maximum water level during the stoppage in the flow of ice.

Vertical line: water level during the first movement of ice.

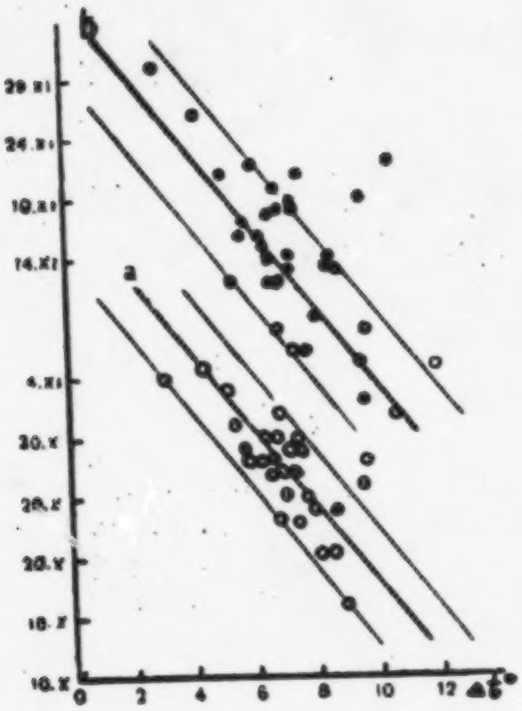

Figure 1. This graph gives the appearance of autumn icy phenomena (a) and the appearance of freeze-up (b) from the change in average air temperature from August to September (Δt). Selenga River at the town of Ust'-Kyakhta. (Novoselov, 1961)

"In order to take into account the description of the peculiarity of developing atmospheric processes, a supplementary argument between the observation of the average monthly air temperature for August and the norm, in the ratio $K = t_i : t_{cp}$.

"If the magnitude of K is greater than unity, this verifies the predominance of the southwest outflow of air masses and, consequently, the conditions present for the later formation of the Siberian anticyclone. If K is close to unity, or less than it, the conditions for the formation of the Siberian anticyclone are normal.

"Thus, a curve is obtained for the forecast of the appearance of ice and freeze-up, taking into account the air temperature for August and September, the certainty of which is 98% (Figure 2).

"The lead-time for a forecast of the autumn icy phenomena is from 8 to 40 days, and for the forecast of freeze-up -- is from 30 to 60 days.

"In order to improve the lead-time in the forecast of the time when autumn icy phenomena appears, especially under conditions of early river freeze-up, supplementary curves are constructed by using the average air temperature for 15 days in September."

Bilello (1964) describes a system for forecasting the date of ice formation. Although not mentioned in the report, the study could have application to autumn ice jamming in reaches without rapids or where flooding does not occur.

"Rodhe (1952) developed a relationship between weighted air temperature difference between the water surface and the air. Rodhe expresses the change of water-surface temperature with time mathematically as follows:

$$\frac{d\tau}{dt} = k(T - \tau) \tag{1}$$

where

T = air temperature
τ = water surface temperature
t = time
k = a constant with inverse dimension of time.

Rearranging equation 1, and multiplying it by e^{kt} gives:

$$e^{kt}\,d\tau + k\tau e^{kt}\,dt = k\,Te^{kt}\,dt \tag{2}$$

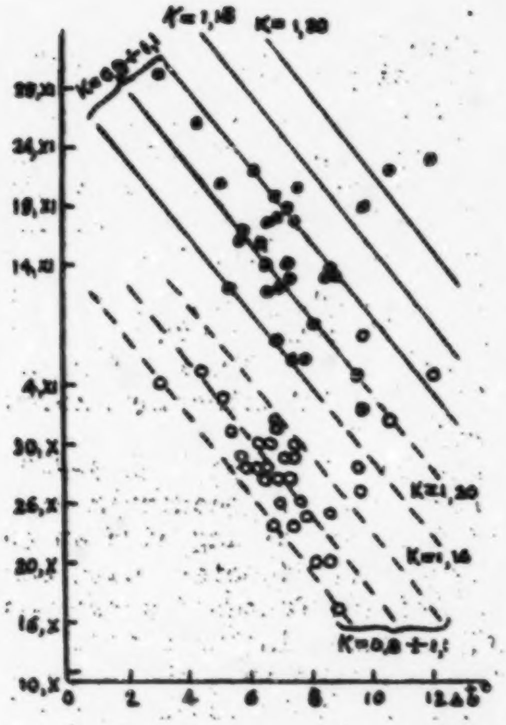

Figure 2. This graph gives the appearance of autumn icy phenomena (dotted lines, white circles) and the appearance of freeze-up (solid lines, black circles) from the change in average monthly air temperature from August to September (Δ t) and the development of K for August.

(Novoselov, 1961)

which can be written in the following differential form:

$$d(\tau e^{kt}) = T \cdot d(e^{kt}). \tag{2a}$$

Integrating eq 2a from t_0 to t_n, we have:

$$\tau_n e^{kt_n} - \tau_0 e^{kt_0} = \int_{t_0}^{t_n} T \cdot d(e^{kt}) \tag{3}$$

where $\tau_0 e^{kt_0}$ is a constant specified by the lower boundary condition of integration.

"By dividing the period t_0 to t_n into n equal and short intervals, Δ t, and representing the air temperature T_v as the mean temperature for the interval t_{v-1} to t_v, eq 3 can be written as follows:

$$\tau_n = \tau_0 e^{-k(t_n - t_0)} + (1 - e^{-k\Delta t}) \sum_{v=1}^{n} T_v e^{-k(t_n - t_v)}. \tag{4}$$

"It can be seen from the above equation that if the period $\overline{t_n - t_0}$ is selected to be sufficiently long, the term containing the lower boundary conditions becomes negligible, and at the same time, $1 - e^{-k(t_n - t_0)}$ approaches unity.

"For practical calculations of τ, Rodhe used a formula of iteration. With the moment t_{n-1} instead of t_0 as the lower boundary, eq 4 may be written as:

$$\tau_n = \tau_{n-1} e^{-k\Delta t} + (1 - e^{-k\Delta t}) T_n \tag{5}$$

or

$$\tau_n = \tau_{n-1} + (1 - e^{-k\Delta t}) (T_n - \tau_{n-1}).^* \tag{5a}$$

---

*The full mathematical treatment of the theory is available in Rodhe's report (1952).

"Athough τ was identified with surface water temperature, Rodhe in the derivation of eq 5a used it as a function of the air temperature. In a later report he compared the correlation between sea-ice formation and air temperature with that between sea-ice formation and sea-surface temperature and found the correlation coefficients to be similar (Rodhe, 1955)....

"Equation 5a provides a method by which the predicted date of ice formation at a particular location can be computed objectively from daily air temperatures. The procedure is to determine by trial and error that value of k in the expression $1 -e^{-k}$ which reduces a weighted air temperature sequence to the freezing point on the exact day ice forms. By associating the time when the air-temperature sequence reduces to the freezing point with the date of observed ice formation, a numerical constant (N) is determined."

Golek (1957) warns of some pitfalls in empirical methods of forecasting.

"It is again underlined that known resumes of ice jams do not preclude possible forecasting of this phenomena due to the following reasons;

1) Lack of observations for the entire length of the river course

2) All building construction for river regulation change the corridors, therefore changing the factors for creating ice jams.

3) Battling with ice jams ruins the possible creating of ice jams, noting that irrelevant operations can create possible appearance of ice jams without natural reasons.

4) Beyond observations verifying appearance of ice jams there is a lack of written reasons which were the cause of the ice jams, as well as the effects of specific ice jams."

Henry (1965) describes ice jam forecasting on the Yukon.

"The capability of ... the ice to jam can be forecast. Flooding occurs in the years when the headwater of the Yukon and Tanana thaw before the middle or lower reaches of the river. The downstream ice is still strong and remains in large sheets or pans which can form the strong jams needed to cause floods.... Flooding in years of light snowfall is common because the ice is thicker and stronger....

"To forecast flooding conditions, the forecaster is primarily interested in a long range temperature forecast for a large area. The strength of the river ice depends upon the temperature.... The most important temperature forecast is for the respective areas of headwaters, middle reaches, and lower reaches of the river.

"The required forecast is for a long term which depends on the general circulation of the atmosphere. The position of the major upper-air trough is most important. If the major trough is in the Gulf of Alaska during late April and early May, the headwaters of the Yukon will warm; the snow melt arriving at the still cold middle reaches will cause serious jamming and flooding. But if a major ridge is over the Gulf of Alaska, then the lower and middle reaches of the river will thaw before the headwaters and thus the channel will be clear of ice and no jamming will occur. A weather forecaster can make successful forecasts by using the 30-day outlook and the 5-day forecast provided by the Extended Forecast Center. He can make a 'no flood' forecast with confidence, but cannot predict the location of the flood because he cannot know where ice jams will occur."

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Ice Modification

Ice modification is an alteration of an existing or latent ice cover to promote free ice passage and thus prevent or remove an ice jam. Techniques include: ice breaking, dusting, thermal regime modification, and explosives. As the summaries in this section indicate, certain techniques are usually better suited for either prevention or removal.

Deslauriers (1965) classifies ice modification into two catagories.

> "Occasional preparatory works (Prevention)
>
> "Advanced awakening or partial destruction of the ice cover at some bad spots in a water course is often an efficient preparation for a coming break-up. The main objective is either to reduce the rigidity of an ice slab, to break an ice pack or to create an open water channel. Breaking operations are achieved by the use of explosives (low speed types being more efficient) or by ice-breakers; melting operations by effects of thermo-chemical bombs, black dusts (captation of solar energy), melting salts, etc.
>
> "Urgency measures (Removal)
>
> "They are often requested for the breakage of ice-jams already formed. The artificial destruction of a jam is ordinarily a difficult and hard operation, and usually a risky venture. Most of the time, the natural evolution and destruction of the ice blockage is completed even before the organization of an urgency measure has been completed. Whenever it can be undertaken with a certain degree of success and without risks of greater damages elsewhere below the affected spot, the urgency measure is to be considered as a venture for responsibility and costly operations. However, in some peculiar spots and for certain types of jams, few successes are possible and some achievements may be sometimes economically realized."

Reports were included on the basis of their pertinence to river ice or ice jams. For example, some reports of ice breaking in arctic areas were reviewed, but are not included here.

Ice breaking

In describing some measures used to prevent formations of ice dams, Balanin and Szcherbakova (1967) mention the use of icebreakers.

> "The destruction of the ice cover by ice breakers and ice-breaking ships developing 450-5400 h.p. is carried out in three delta arms of the North Dvina for more than 40 km upstream the river in the range of the whole width of the river channel.
>
> "During the time of ice drift the ice breakers are kept on duty to guarantee free passage of ice and prevent the formation of ice dams."

Ice dam removal is by icebreakers and explosives: "The work should be done with the help of not less than two ice breakers and should be carried out upstream. It consists in cutting off and floating down certain masses of ice, first of all from the central part of the ice dams. There should also be made explosions there."

They conclude that: "The use of ice breakers in the delta and ice cutting machines in the upper reaches of the North Dvina with the above mentioned amount of necessary works (dusting) gives an almost safe guarantee of preventing innundations due to ice dam formation."

Stakle (1936) prefers ice-breaker-tugs over explosives. "The best way to avoid ice-jams is to break up the ice by artificial means with ice-breakers (ordinary tugs) before a natural break-up takes place. This has been done regularly every spring in the lower reaches of the Daugava since the eighties, thereby avoiding ice-jams in the Riga harbour districts. All other attempts to overcome ice-jams by means of manual labour, blasting and shelling have proved unsuccessful: in comparison with the enormous mass of ice, methods such as these are trivial. During the last few years ice has also been broken up by tugs in the lower reaches of the Lielupe and Venta."

Ice breaking methods are also described by Wemelsfelder (1957). 'In the Netherlands only one method of ice control is ordinarily used, vis. breaking by ice breakers....

"Bursting of dikes, caused by ice dams and accumulations of drift ice frequently occured in former times. At present the consequences, as a result of the rapidly grown density of population, would be disastrous.

"It is always attempted to get the rivers, especially the Waal, ice free before thaw sets in....

"In the first place efforts are made to try and prevent the ice being packed in the lower course of the Waal. Due to the tidal motion four times a day a total standstill of the stream takes place here. This reach of the lower course comprise 5 to 10 km near Werkendam or Gorinchem. The turning of the tide sometimes lasts more than 2 hours. The river here is 400 m wide. Practically no water is seen between the 10 to 15 cm thick flakes of ice during the standstill of the stream.

"If frost does not exceed 8 to 10° C, it appears possible to prevent the pancake ice--being-drifted together--to freeze tight. This is achieved by the incessant zig-zag movement of three or four ice breakers among the pack ice. The ice mass is carried along to sea by the following ebbtide.

"At a temperature below--12 to--15°C this action of the ice breakers is no longer sufficient. The turnings in the tide at night are especially critical, because ice breaking is very dangerous then. Only where powerful spotlights are available, can ice breaking take place at night. If the ice has formed a fast cover it is no more carried along with the following ebbtide. The water is running to sea below the ice. The ice cover is expanding rapidly upstream, at a speed of 1 km an hour. Ice breakers launch their attacks on the ice cover from the downstream side. By acting so, the ice can be carried along to sea with the stream.

"The Waal is about 300 m wide. Two or four ice breakers attack the ice one after another in the first line. Large ice fields then float downstream. Two ice breakers in second line break up these ice fields and prevent the formation of pack ice coverings downstream.

"The thickness of the pack ice nearly always exceeded 30 cm, but frequently even 50 cm and more. Here and there ice is piled up to a thickness of several meters. Locally the ice sometimes rests on the bottom of the river, and can be pressed up to 4 meters above the original water-level. Thicknesses up to 8 meters have been recorded.

"The breaking up of these ice heaps brings about great masses of floating ice. The river surface downstream the dam becomes almost fully covered by floating ice, carried away by the stream. In case long river stretches have already been broken up and when severe frost is still continuing, this floating ice shows a tendency to freeze tight downstream in the tidal region. Of course these events must not be allowed to develop because repairing of damaged ice breakers must take place downstream at Dordrecht. So ice breakers are incessantly patrolling the tidal region. Moreover at least 2 ice breakers are necessary on every 20 km of river stretch. In this way the number of ice breakers in use increases, as breaking goes on upstream. After ice breaking had covered 100 km, it occurred that in addition to 4 ice breakers in the frontline, still another 10 were needed to guarantee an uninterrupted removal of the already broken ice to sea.

"The discharge of the Rhine is, as a rule, low during severe frost and the depth of the river small. Ice breakers are hindered by the limited depth, and damaged by ice dams and irregularities in the bottom in consequence of this. So ice breakers may run aground on unexpected shallow places, especially immediately downstream from an ice dam. In such cases ice breakers can reach the ice dam only in a limited number of places or not at all."

"There are four types of ice breakers in use, viz.:

1. The type sliding on ice and breaking it by the weight of the vessel.

2. Tugs provided with an ice plough of such a shape, that the tug slides on the ice and breaks it by weight.

3. Tugs provided with an ice plough of such shape, that the plough slides under the ice cover and the ice is broken by the lift of the vessel.

4. Ordinary tugs provided with reinforced frame and an ice lining.

"In most cases tugs provided with a separate ice plough are used. Besides solitary ice breakers, pack ice is often broken by 2 strong tugs towing freighters or by power-driven vessels."

The types, uses and disadvantages of icebreakers are described by Siegfried (1957).

"The type of ice breaker used on the canals of France are essentially motorized tow boats. They are capable of breaking ice up to about 15 centimeters thick. Beyond that thickness the risk of injury or damage to the ship becomes very great. If the ice is over 25 centimeters in thickness the operation becomes practically impossible. The second method used to break the ice on the canals is to tow a barge through the canal. The ease with which the ice can be broken is a function of meteorologic conditions and local experience. This method of icebreaking is generally employed early in the freezing season or shortly before the advent of the spring thaw.

"In the estuaries the motorized tow barges are used as ice breakers. As in the canals they are fitted with ice plows. Because of the thickness and hardness of the ice cover some damage is sustained by the ships. When the ice thickness is such that the tow barges cannot break it, explosives are used."

Two papers describing early French use of icebreakers (reinforced towboats) are by Rigaux (1894) and Pasqueau (1880).

According to Vandervelden and Sterling (1957) icebreakers have been used on Belgium rivers to delay freeze-up and accelerate break-up.

Lambor (1957) describes the use of ice breakers to combat ice barriers on some European rivers. He claims that on the Vistula, ice jams have not caused overflowing of the dyke system since their use.

Hinz (1930) mentions the use of icebreakers in the tidal district of the lower Elbe River.

Horvath and Laszloffy (1957) report that the use of icebreakers on the Hungarian Danube is ineffective due to jams of broken ice developing beyond the country's border. They advocate river regulation as an effective method of jam prevention.

In another paper, Laszloffy (1948) gave further comments on the use of icebreakers.

> "The employment of icebreakers aids in retarding the freezing of the river or in dislodging the arrested ice, but, in the presence of exceptional thermal conditions, this means is offset sooner or later by nature."

On the other hand, Karolyi (1963) states that the Hungarian icebreaker fleet (7 vessels) successfully prevented the development of many ice jams and accelerated the breakup of others on the Danube in 1963.

Lambor (1957) feels that icebreaking is most efficient in keeping waterways navigable, but the method is too costly. His study included Central and Eastern European rivers and he recommends thermal pollution as a permanent method of ice control.

Van Der Kley's (1965) tests in the Netherlands indicate that icebreakers are less expensive for removing ice jams than explosives.

Laktionoff (1957) mentions icebreakers as one means to combat ice jams and considers possible future refinements.

> "The experimental use of icebreaking vessels on inland navigable waters of the USSR has shown promising results and has made it possible to define conditions that should ensure in future their still more effective application, such, for instance, as: the necessity of having water-heating and steam producing facilities of a greater capacity to successfully combat the sludge, the need for powerful winches, fore-and-aft, for special ice cutting devices, for increased engine, for a lighter vessel draught, for bow-and side-placed cisterns to permit variation, at will of a longitudinal and lateral trim of vessels, thus facilitating for them to negotiate shoals." The report does not offer operational details, and several other types of preventative measures, such as dusting, are recommended.

Antrushin (1956) reports on a common disadvantage of icebreakers in the estuaries of northern rivers in European Russia: "Large ice breakers can not be used to combat ice jams because some sections of the rivers are too shallow to allow their passage."

He also feels that dusting is less costly than the use of icebreakers.

"Economically effective methods appear from examination of the data. In 1955 ... the cost was 60 times less than that of renting ice-breakers, opening the same (size) field of ice in the narrow navigable canal of Maemaksa...."

A Canadian icebreaker which is similar in design to the standard European types (Wemelsfelder, 1957; Siegfried, 1957) is described in a recent news article (Ross, 1967).

"The device, a radical departure from traditional icebreaking methods, was tested successfully in March against ice in Lake Ontario that was up to 18½ inches thick.

"Called the Alexbow, it operates on the principle that it is much easier to lift ice against relatively unresisting air than it is to crush it down against incompressible water."

"The Alexbow, similar in appearance to a snowplow, is designed to lift and throw ice onto the unbroken ice surface on both sides of the channel it has cleared so ice chunks won't damage cargo ships following astern.

"The point of the 5/8 inch concave steel bow glides under the unbroken ice, exerting upward pressure so that the ice breaks and rides up the blade slope and rolls off the blade's swept-back wings.... The bow makes contact with the ice without shock, since the ice rides up the bow on a cushion of water."

"The prototype is a free-floating, barge-like vehicle of 92 gross tons. Its blade is 14 feet high, and its point rides two feet under water....

"In Lake Ontario trials near Kingston, Ont., it was fastened by steel cables to a 219-ton, 1,320-horsepower tugboat which delivered an estimated 900 horsepower at the trial speeds of 2½ to 3½ knots.

"In March trials, it broke a channel more than 30 feet wide thru 12 to 14 inch ice. In early April it cleared a channel thru ice which was up to 18½ inches thick.

"... The prototype free-floating bow pushed by a tug or small ship is one of four possible configurations. Others are (1) a self-powered Alexbow; (2) a detachable bow that could be fitted on conventional ships; and (3) an Alexbow designed into the bow of a ship during its construction."

Stothart and Croteau (1965) mention the use of icebreakers at Montreal. They state that their use did not guarantee an open river every year. No details of operations are given.

Watson (1959) and Bullock (1959) describes the operations of conventional icebreakers in Canada.

The use of icebreakers on the St. Lawrence is mentioned by Small (1955).

> "Below Lake St. Peter the river does not ordinarily freeze over under present conditions, but sometimes large fields of bordage ice, loosened by the rise and fall of the tides or otherwise, may move out into and block the channel. If left undisturbed, ice from upstream will lodge against these ice fields and freeze into serious obstructions. Timely action by icebreakers easily keeps the channel open."

Williams and Williams (1926) discuss some aspects of the design of early icebreakers. The early operation of icebreakers on the St. Lawrence River are included.

Waas (1963) describes some design aspects an operational testing of the German ice breaker 'Josef Langen'. The vessel is a shallow draft icebreaker specifically designed for operation on the Rhine River.

> "Icebreakers are used during hard winters in the mountainous reaches of the Rhine against ice obstructions in order to guarantee drainage and prevent a flood."
>
> "The Rhine between Mainz and just above Bingen is very wide and thus the area over which ice can build up is large. Below Bingen in the mountainous stretch the Rhine is very narrow, especially near the Lorelei. Here the floes are pressed together whenever there is drift ice. An aggravating factor is that the speed of flow near the Lorelei is very low as the water is very deep. The floes therefore become easily stuck fast here. The ice obstacle then grows quickly up-river and soon reaches shallower places, where the floes coming from up-river pile-up and settle to the bottom. In this way a dyke of ice is formed.
>
> "The icebreaker thus has the task of preventing the settling of the ice as long as possible... when it can no longer succeed, it has to break through a solid ice sheet. In other cases it has to loosen, break up and disperse the mass of pack-ice built up from the bottom. Icebreakers in general can only attack ice obstructions in an up-stream direction, they have therefore to proceed through an area where the water level is very low.
>
> "A shallow draught of at most 1.30 m. has proved to be an absolute requirement for Rhine icebreakers.
>
> "The water speed becomes very high in the open channels that build up between the ice masses that are still fast. The icebreaker has therefore to achieve a speed of 18 km/hr. in shallow water."

Waas next describes some undesirable features of previous designs.

"The icebreaker 'Nobiling' ... was designed on the basis of experience gained with 'Reiher', which dated from 1935. They closely resembled one another, in fact the only difference was in the shape. The forecastle was made wedge-shaped because the spoon shape of the 'Reiher' had not proved effective in strong pack ice (figs. 4, 5)....

"The 'Nobiling' proved itself in general, especially as far as its shape was concerned.... The main objection was that it failed to break quickly through the ice barrier that was building up above the Lorelei, and prevent the damming-up of the river.

"The most important conclusions from tests on the 'Nobiling' as an icebreaker, were:

1. The 'Nobiling' often became stuck when making hard runs at strong ice and could not free itself even with the strongest reverse thrust....

2. In a small channel with a strong current the boat often could not gain enough speed to ram into the ice with sufficient force. The power was also insufficient to break the resistance of a layer of ice.

3. Reversing the engine when repeatedly ramming the ice, and working the helm, took far too long....

4. Cooling of the diesel engines was often impaired, as the cooling water entry port became clogged by ice-sludge. This seriously decreased its usefulness for icebreaking service....

"Planning a new type of icebreaker

"... The required increase in engine output without increased weight could only be provided by light high-speed diesel engines.... As a next step it seemed unsatisfactory in such a shallow - going ship to stress the already unfavourably loaded propellers (250 hp with a dia. of max 1.1m) still more. The desired increase in output pointed towards a triple-screw vessel. But the three-screw arrangements examined (each of 250 hp) needed too much space in the engine room. There were furthermore objections to the employment of three screws on an icebreaker whose screws often run in ice.

"... Two 600 hp ... engines were used ... to transmit their output to the propellers benefiting from as large a propeller diameter as possible by means of a tunnel arrangement of the poop.... The total surface area of these two propellers is indeed a little smaller than that of three propellers each of 1.1 m. dia., but tests showed a ramming thrust of more than 9t. for the 2 x 600 hp installation with 1.3 m. dia. propellers. Thus the 3 x 250 hp installation with 1.1 m. dia. propellers was not inferior in weight and dimensions but also in terms of ramming thrust, as it could only deliver about 6.3t. The maximum speed also proved to be advantageous for the two-propeller ship, at appr. 18 km/hr."

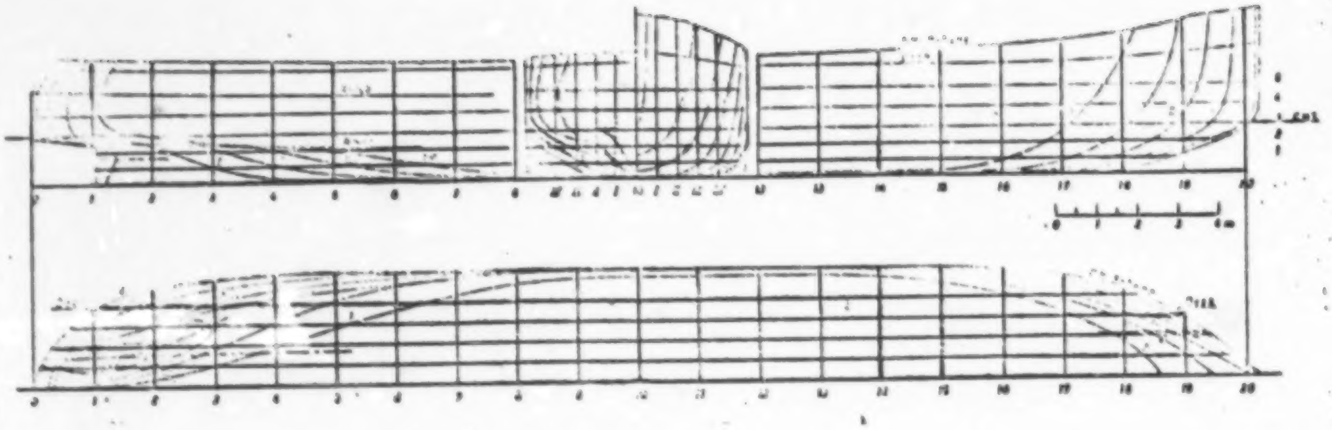

Figure 4. The icebreaker "Reiher", with spoon-shaped forecastle allowing the icebreaker to slide easily on to a flat ice surface, but which is too blunt for pack ice or ice sludge. Its vertical sides and parallel midships section promote speed but also tend to become stuck in the ice. Key:Schanz - bulwark; Knick - break in a curve; CWL - central waterline.

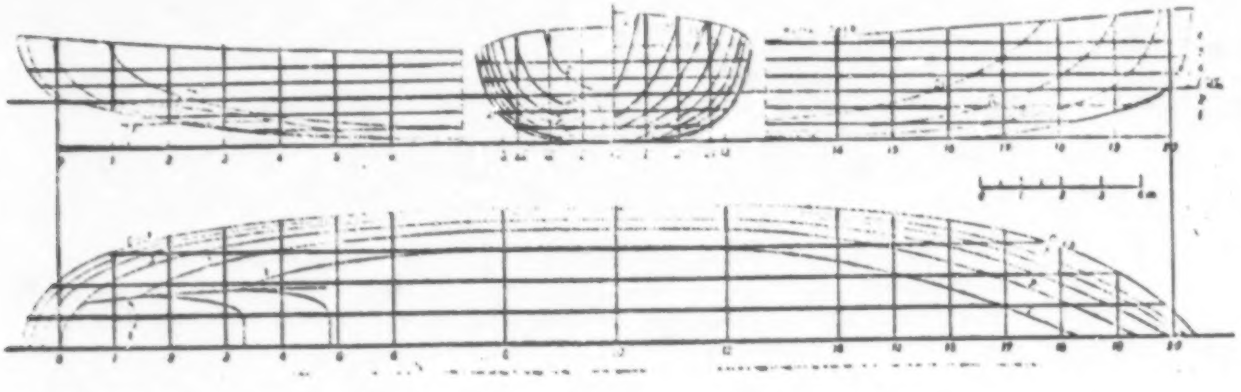

Figure 5. The icebreaker "Mobiling" with wedge-shaped forecastle, which is superior to the spoon-shape in pack ice or ice sludge. The egg-shaped section below the waterline does not easily become fast; the loss of speed it causes has to be accepted.

(Waas, 1963)

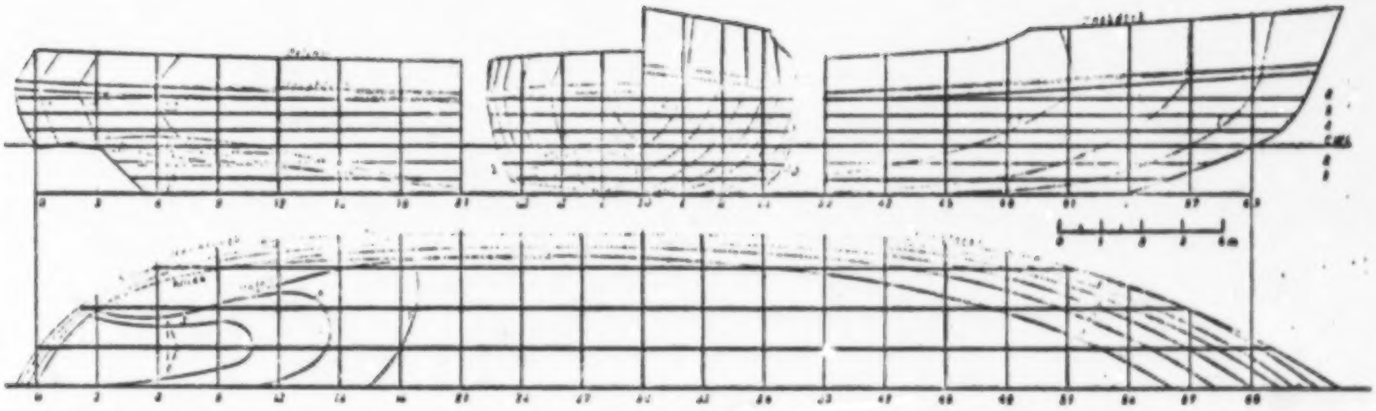

Figure 6. The icebreaker "Joseph Langen" with wedge-shaped forecastle and egg-shaped section below the waterline. The stern is strongly tunnelled to house the large propellers can thus be three times as large as those of the "Reiher" or the "Nobiling". The tunnel is exceptionally long behind the propellers and is deep so that the ship will have a good streamlined shape when steaming backwards. The long deadwood prevents too strong an interference between the screws and promotes steadiness. Key:Reling - rail; Hauptdeck - main deck: Backdeck - fore-deck. (Waas, 1963)

"A special advantage of the adjustable propeller for a two-shaft icebreaker is that the direction of rotation of the adjustable propeller remains the same for forward or reverse movement, so that both always act in an outward direction. In this way drifting ice-floes will not be drawn between the propellers when reversing. The other factor in favour of the adjustable propeller was its capacity for quick and frequent reversal."

"The difficulties that have occurred with ice sludge clogging the cooling water entry port should be overcome by the outer shell system of cooling. It was not easy to place the necessary surfaces for engine cooling, compressor and auxiliary engine cooling, in suitable positions on the outer hull. Special problems were caused by the vibration to be expected because the flow against the propeller is very uneven and the joints of the stern have to be relatively lightly built. An elastic, supercritical propeller suspension system as developed by Grim (1960) was chosen for the first time on an icebreaker."

"The most interesting innovation is probably the Hitzler stamping machine plant. So far the only plants used on rivers have had a rotating eccentric flywheel in both forecastle and stern with a maximum unit power of approx. 12% of the ship's weight. This was not sufficient for the specially difficult conditions on the Rhine. In the meantime, however, coastal ice-breakers had had experience with a more effective plant which was completely concentrated in the forecastle. These plants were developed for river icebreakers, and the 'Joseph Langen' provided with one. A periodic force of approx. 38% of the ship's weight - about 50 t. - can be achieved with these plants."

"The results of the battle against the ice in 1963

"The 'Reiher', 'Nobiling' and the 'Joseph Langen' set out from St. Goar, below the Lorelei, to keep the ice moving in the critical narrow passage as long as possible. The 'Reiher' and the 'Nobiling' quickly got stuck in the thick ice pulp and even drifted downstream with the ice-field, but the 'Joseph Langen' steamed up - and downstream without trouble, although rather more slowly, and thus kept the ice drift moving. Previously the drift-ice would become lodged after 3 or 4 days, but this time it kept moving until the seventh day. The jamming of the ice could not be completely prevented, but the 'Joseph Langen', which was introduced immediately, managed to push through the same day to Betteck and then further, to Kammereck....

"The stamping machine in particular proved its value.... The ship would quickly remain stuck in the ice when the equipment was not used, but with it it could continue its course slowly through the drift ice.

"Each oscillation resulted in an advance of ... about 10 cm.; this is a speed of 0.8 km/hr for a frequency of 140/min.

"The 'Joseph Langen' was able to apply a new technique for widening the channel between especially high walls of pack-ice, which here rose up to 3m. above water level and partly rested on the bottom; the technique loosened large masses of ice in record time. The ship would work itself into the ice at right angles to the current until it had loosened a large pack of ice downstream of its bows. This method of working was only possible using the stamping machine.

"There were some limits to the continuous course of the 'Joseph Langen' and in these cases it had to resort to ramming. But even when it had run into an especially strong ice obstacle, it would work itself out of and free of the ice quickly and easily thanks to the stamping machine. In one case when it tried to crash through an ice-barrier to an open channel behind, it got stuck on the barrier with its screws in the air. Gradually it slid into the open water in front, thanks to the stamping."

"When the first channel in the river was made, the icebreakers worked to enlarge it. The 'Joseph Langen', with the help of its stamping machine, cut large strips from the fields of pack-ice that surrounded the channel and that in places tower up to 2.5 m above water level. A further advantage of the stamping machine plant showed up: the ice breaker could, while stamping, steam at a sharp angle into the pack-ice without sliding away to one side....

"... In contrast to the older icebreakers the 'Joseph Langen' can also:

1. break light ice downstream;

2. steam continuously in medium ice without having to ram;

3. ram in heavy ice at full acceleration without getting stuck;

4. cross short high pack-ice walls even though it is completely out of the water at times;

5. separate strips from the pack-ice at a sharp angle;

6. penetrate into very thick pack-ice at right angles to the current, and thus break loose large packs of ice."

Other papers dealing with the design aspects of icebreakers are given by Simonson (1936), Crighton (----) and Ferris (1959).

Bock (1957) discusses problems in breaking river ice and ice jams in power plant ponds. "The most simple way of just leaving in peace the ice cover developing in the pond doubtless results in the smallest quantity of ice by its protection of the water current from further refrigeration. However, the possibility of simply waiting for thawing of the ice coat by itself largely depends on the question as to whether navigation can be discontinued during the freezing and thawing periods. Further, if retaining the ice cover in the pond, it is essential to pay the utmost attention to the question as to whether upstream from the first unit or in big tributaries opening into the river within the power station system, there is any probability of ice impacts being formed, whose removal may cause very serious implications when impaired by the ice cover."

He continues by providing design information on the icebreakers.

"The power plant management had two ice breakers with an engine capacity of 400 HP at their disposal which worked satisfactorily in general. The spoonlike form of the ship in conjunction with a rolling equipment made it possible to successfully attack even heavy ice accumulation. The technical data of the two ice breakers are as follows:

Overall length	27.75 m
Spacing of frames	6.50 m
Lateral height	2.40 m
Average draft without water ballast	1.43 m
Average draft with water ballast	1.72 m....

"The adjustable propellers were liable to break down in intensive use....

"The rolling equipment has proved to be extremely useful....

"These faults will be remedied for the two further ice breakers now under construction. Their technical data will be as under:

Overall length	29.15 m
Spacing of frames	6.50 m
Lateral height	2.80 m
Draft without water ballast	1.60 m ...
Capacity	750 HP

"The rolling equipment with two rotating weights of 3.5 to 5 tons shifted by 180 degrees will be individually driven, contrary to the first two ice breakers.

"Efficient working with ice breakers will principally be carried out in upstream direction only. Scoured out channels must be sufficiently broad and have a current strong enough to carry off the broken ice.

"Bottlenecks are to be avoided in such channels as far as possible; should it not be feasible to remove them immediately for some special reason, for instance owing to very unfavourable and irregular ice covering, it is essential to have a second ice breaker available downstream from the bottleneck, which is able to break through an accumulation from the other side in case of emergency. It is important to remember this experienced fact and to refuse to try to attack apparently dangerous

> ice obstacles prior to having all downstream ice accumulations not only broken up but removed in full."

The propulsion and auxiliary machinery of wind-class icebreakers is described in the Engineering Journal (1950).

Granbois (1955) does not advocate the use of ice breaking tugs on power plant reservoirs. Kanavins (1944) feels that icebreakers were totally inadequate in attempting to reduce ice jam problems at the Keggum power plant on the Dvina River. According to Strauch (1954) ice breaking can be used to prevent ice problems near power plants.

The Rock Island District, Corps of Engineers used a towboat to successfully break an ice jam on the Mississippi River at Davenport, Iowa (Engineering News-Record, 1966).

> "After a 13-day battle the Corps of Engineers ... broke a 10-mile-long ice jam that had plugged the Mississippi River at Davenport, Iowa....
>
> "... The Corps brought in two big towboats.... While one kept the ice from jamming up the river behind them, the other pushed a big empty barge up onto the ice at the downstream end of the jam. The weight of the barge broke up the ice, then the barge would be withdrawn to let the free ice flow downstream. Working around the clock, the big towboat finally broke through the key point in the jam, a narrow rock cut at a bend in the river.
>
> "When the big boat finally smashed through, the deluge it released forced the captain to back downstream about 4 miles. It took three assaults into the raging channel before the massive jam was declared broken."

Kienitz (1967) mentions that icebreaking by tugs and towboats in the Mississippi can have adverse effects.

> "One difficulty is that if a channel is opened, ice from upstream tends to pile up at locks and is difficult to clear away. The best way now known to clear it out is with poles, a slow, laborious job, when a tow shows up."

Aune, Beaudin and Borrowman (1957) discuss ice breaking operations on the Mississippi River.

> "Ice breaking operations by the United States Coast Guard were employed during the period from 1947-1948 to 1954-1955 and consisted of the use of 3 to 4 powerful river towboats.... In this operation some use was made of an 'Amsterdam Plow' ... a large plow-like steel prow fixed to the head end of an empty or partially loaded 35 foot (10.6m) wood barge. The width of this 'Plow' is about 8 feet (2.4m) wider than the barges, thus

reducing ice friction on the sides. The use of this type of plow is satisfactory in clear ice; however, navigation is most concerned with pack ice where it is not considered as efficient or maneuverable as a barge without such an encumberance.

"In periods of protracted cold the lesser powered towboats have considerable difficulty in penetrating the heavy ice packs and at times become immobile. Assistance to such tows is provided by other more powerful towboats that would be held up by such stalled tows all to their mutual benefit."

Icebreaking operations on the Niagara River are described by Foulds (1964).

In 1962, "The boats available were small, thin-hulled and under-powered for the job, but did a remarkable amount of useful work principally through wave action."

Later in that year "Two 35-ton icebreakers were constructed.... These boats are very strongly constructed, are 40' long with a beam of 14 feet, draw three and one half feet, and are powered by twin engines totalling some 450 horsepower. Radio communication is provided to the River Control Office for co-ordinating gate movements in the dam with ice breaking activities. Both boats are equipped with radar for navigating in bad weather, and as a safety precaution they normally operate together."

During the 1963 winter: "The east river channel was kept open by the ice breakers but the size of the opening was reduced from 1,000 feet to about 400 feet."

Later in the year: "It proved to be impossible to operate the ice breakers under these (weather) conditions and the east channel around Grand Island became ice covered with the west side remaining open....

"The east river was effectively re-opened by March 1 chiefly through the efforts of the ice breakers even though their effectiveness was hampered severely by the shallow depths.... In accomplishing this task one huge piece broke off and swung around across the Pool creating a bridge very similar to the previous year, however, the ice breakers were able to split it into smaller pieces in a matter of a few hours...."

In a subsequent article on Niagara ice jam control (Foulds, 1967), he further describes ice breaker operations.

"During periods when the daily temperature averages 15° F or less, the boats are used almost constantly to break the river ice into pieces which will skim through the 100-foot width sluices (of a control structure)...."

"An ice breaker in the lower river is being used on an experimental basis to prevent the formation of an ice cover over the portion of the river between the power houses and Lake Ontario. If an ice cover becomes established in this area it assumes massive proportions and therefore the ice breaker has been selected accordingly. The present vessel weighs 400 tons, is 95 feet long with a beam of 30 feet, draws 12 feet and is powered with twin engines totalling some 3,000 horsepower."

In describing icebreaking operations during the winter of 1964, he relates: "Iceballs were created in Lake Erie of sufficient strength to survive the trip through the high velocity rapids section near the Peace Bridge and travel down the river to ground in the Grass Island Pool in 12 feet of water. In order to remove the iceballs, it was necessary to split each of them in half with the ice breakers, and as there were several thousand iceballs and only two boats, it will be appreciated that this operation took some time, during which more ice was being fed into the Grass Island Pool from the lake. As a matter of interest it is necessary when splitting one of the iceballs to ensure that the ice breaker has enough momentum to ride right over otherwise the boat becomes marooned on top. In addition, the iceballs contained rocks, wood, and other debris which were a little hard on the propellers."

Lank and Oakley (1959) discuss the operational and economic factors of nuclear powered icebreakers. Alexandrov, Afrikantov, Brandaus, Gladkov, Gnesin, Neganov, and Khlopkin (1959) describe specifications of the atomic icebreaker Lenin.

Icebreaker operation is discussed by Thiele (1959). Effective use of a vessel, on both the Great Lakes and in polar regions, is stressed.

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Dusting

Dusting refers to spreading solid material on an ice surface to accelerate melting. Spreading is commonly accomplished with aircraft and materials vary widely but are selected to lower the ice surface albedo. This technique usually is employed on river ice and not specifically on ice jams.

Several reports dealing with the meteorological parameters, particle size, material type, etc. involved in dusting were reviewed. Williams and Gold (1963) summarized a comprehensive study on dusting by stating: "The application of suitable dust to an ice or snow surface decreases its albedo and increases the amount of short-wave radiation absorbed. The associated additional heat will increase the surface temperature and may cause the snow or ice to begin melting before the normal melt season. An increase in the surface temperature will also increase the heat lost by long-wave radiation, convection, and sublimation. If the average air temperature is too low, the increase in the heat losses will offset the increase in the heat received from solar energy and no melting will take place. This places a natural limit to the amount that the break-up period can be advanced by dusting. The length of this period is influenced as well by the amount of incoming short-wave radiation available at a site during the day and the thickness of the ice.... The amount by which break-up can be advanced will vary from year to year because of natural variations in air temperature and ice thickness and incoming short-wave radiation.

"The amount by which the albedo of a surface is reduced by dusting is probably directly proportional to the actual area of the surface covered by the dust. For a given density of application (e.g. 100 tons/sq mile) the actual area covered by the dust varies inversely as the average diameter of the particles and the density of the solid from which the dust is formed. This indicates that the smaller the average grain diameter and the lighter the solid, the greater will be the coverage for a given weight of dust. The action of wind and melt water probably places a lower limit to the size of particles that can be used. Field experience indicates that the practical range in average grain diameter is 0.1 to 2.5 mm.

"The maximum amount by which the albedo can be reduced depends upon the albedo of the dusting material. Most naturally occurring dark materials, such as sand, soil, coal dust, soot, have an albedo of about 20 per cent. Once melting has advanced to the point where the dusted surface is covered with water, the albedo of the surface will probably be determined by the water and not by the dust and its density of application.

> "The cost will probably determine whether dusting is practical at a particular site. Sufficient information to assess the cost is therefore required.... Further information is required on the availability and characteristics of suitable economical dusts and on the equipment and techniques to spread them. The dependence of the change in albedo on the density of application and average grain size and density of the particles should be investigated further.... Experience with the use of dust should soon be obtained through full-scale field trials."

An extensive reference list is also given in the above report which cites the study of Arnold (1961). The following quotation describes his testing program.

> "During the summer of 1959 the author conducted experiments on snow, sea ice, and lake ice surfaces in an attempt to accelerate their rate of melting by artificial dusting. Seven different types of materials were used, differing in particle size and in the presence or absence of salt or sand. Each of these materials was spread in amounts of 100, 300, 500, 700, and 1000 grams on squares one square metre in area. This gave thirty-five squares to study on each of the snow, sea ice, and lake ice surfaces.
>
> "During the summer, repeated measurements were taken in each of these squares, using a level and rod to measure the departure of each square from a system of reference stakes. Comparison was also made with untreated areas, which served as a control. Cores and stereoscopic photographs were taken in each square of the sea and lake ice surfaces, illustrating the penetration of the dust into the ice surface. Meteorological readings are available at three-hour intervals in the areas studied."

The above study must be considered as a qualitative guide only due to the absence of global radiation measurements. The importance of this variable was stressed by Williams and Gold (1963).

In a recent study Williams (1967) concludes that weather, snow and ice conditions, and dusting technique are the three main factors in dusting.

> "Weather conditions
>
> "Dusting snow or ice covers to increase the rate of melting of ice is not very effective if the minimum daily air temperature falls much below 32°F. This conclusion applies to all latitudes. Ice dusting is thus most effective during the normal melting period. Dusting much before natural melting begins is usually not worthwhile because the dusting period is usually followed by periods of freezing weather which will freeze the melt water produced....

"Small amounts of new snow, which might in weather records be classified as a trace, can effectively cover dusted areas and prevent increased melting by dusting....

"As air temperature, snowfall, and solar radiation at a site vary greatly from year to year, so will the success of dusting. Variable weather conditions might be the factor that will discourage regular, large-scale, ice-dusting operations. In the U.S.S.R., large-scale dusting operations were reported to be successful on an Arctic Bay in 1959 (Peschanskii, 1963), but the next year, at the same site, the operation was only partially successful because of drifting snow and low air temperatures with cloudy conditions.

"Snow and ice conditions

"The way in which natural ice melts must be considered when assessing the usefulness of dusting to increase the rate of snow- or ice-melt. For example, fresh-water lake ice has a relatively high albedo for much of the ice-melt season. Dusting the surface, therefore, can decrease the albedo and hence significantly increase the melting rate.

"The depth of water that accumulates in the dusted plots can limit the effectiveness of dusting. The maximum depth in these experiments was 8 in. (20 cm) at Ottawa and about 18 to 24 in. (45-60 cm) in the Arctic....

"Drainage holes can develop and extend through the ice cover at dusted sites. Melt water will then drain through the holes and melting will be faster than at sites where drainage water accumulates. Under these conditions, part of a dusted area will clear of ice more rapidly than other parts. This result might be of practical significance in large-scale ice-dusting operations.

"Dusting techniques

"Clearing the snow from an ice cover can increase the rate of melt effectively if the snow cover is deep enough to delay natural melting and if the underlying ice cover has a naturally low albedo (black ice). Under some conditions the weight of snowbanks at the edge of the cleared area will cause the ice to deform and accelerate its decay due to flooding. The snow-clearing technique should be limited to regions where late spring snowstorms are infrequent, and the snow cover can be easily removed.

"Almost any dark material applied to an ice surface will absorb radiation and increase the rage of melt under favourable weather conditions.... The density of application will depend on the particle size and how evenly the dust can be applied. In practice the density of application will range from 0.04 to 0.08 lb/sq ft (200 - 400 gms/sq m.).

"Dyes and powders applied in the form of sprays to ice covers that are porous are not as effective in the early stages of melt as sands or similar dusts because they penetrate the ice leaving a surface with a high albedo. As the melt season progresses, however, solar radiation is absorbed by the spray beneath the ice surface and thus increases the melt rate. At sites where the cost of transporting and applying dust is high, sprays have an advantage over dusts because much less material is required.

"Pumping a thin layer of bottom mud onto the ice cover of shallow lakes or rivers in an effective means of increasing the melt rate of ice.

"The choice of technique will depend on cost and local site conditions.... The choice of technique will also depend on the problem that is to be solved, e.g., increasing snow or glacier runoff, extending the navigation season, or preventing ice jams on rivers. Past weather records and information available on the problem (such as past break-up records, site conditions, etc.) need to be studied to determine if possible benefits warrant the estimated expenditure...."

Skorik (1960) describes some Russian tests on dusting substances. His conclusions are given below.

"1. Dusting of the ice surface with hard insoluble finely-dispersed materials promotes the thawing and destruction of the ice.

"2. The rate of thawing and destruction of the ice cover depends on the nature and degree of subdivision of the dispersed material as well as on the density of dusting of the ice surface with this substance.

"3. Dyeing of natural sand with Prussian blue and aniline black (0.5,1 and 2 g per 400 g sand) promotes its destructive effect on the ice, although to a less extent than could be expected on the basis of the separate effects of sand and dye. The destructive effect of dyed sand on ice is not in fact the sum effect of its components. On dyeing the sand, the dye sticks to the sand particles (thereby increasing the colour intensity and radiation absorbed) and also forms dye films on the sand particles which results in decreasing the dispersity of the dye (thereby reducing the effectiveness of the dye of increasing absorption of solar radiation of the dye).

"4. The action of coal dust (particle size less than 0.5 mm) on ice has several features distinguishing it from other dust-like materials;

(a) 500 g and even 250 g of coal dust spread over an ice surface area of 25m^2 destroyed the ice cover more effectively than did 10 kg of sand.

(b) the coal just penetrated the ice to a depth of 47 cm in spite of the 10 -15 cm thick layer of water.

"5. In the course of the experiment, the dye Prussian blue which was applied directly on the ice, as well as that used for dyeing sand, gradually changed colour from blue to green and even rust-brown. The dye aniline black did not change its colour throughout the entire experiment. Prussian blue was twice as effective in the destruction of ice than was aniline black when each was applied directly to the ice surface. The action of Prussian blue in dyeing sand was considerably weaker than that of aniline black used for the same purpose.

"6. Since the radiation absorptivity of hard, opaque subdivided materials depends on their degree of subdivision as much as on their colour, in order to promote the destruction of ice it is more practical to use small quantities (several grams per square metre) of highly despersible substances rather than large quantities of substances with low dispersity, e.g. sand. The existing standards for dusting the ice cover with coal dust in order to melt channels in the ice may be decreased up to several hundred times if the particles size is correspondingly decreased."

Cook and Wade describe the results of dusting to prevent ice jams near Fairbanks, Alaska in a report by the Rock Island District, Corps of Engineers (1967).

"The Chena River ... flows through the town of Fairbanks, Alaska, just upstream from its confluence with the Tanana River....

"Ice jams on the river can result from a combination of several factors; early runoff from the heavy snowpack, relatively stronger ice on the Tanana and loose ice at the mouth of the Chena. The ice on the Chena, historically, breaks up before the Tanana, resulting in floating ice attempting to enter the Tanana before there is space for it....

"Theoretically, dusting appears to be a feasible technique for reducing the danger of ice jams in the Fairbanks area. The total radiant energy received on a clear day in the Fairbanks area has been measured (Sargent and Gotaas, 1964) and found to be approximately 480 calories/cm^2 at the beginning of May. For melting snow, the albedo ... varies from 40 to 60%. Dusting appears to make it possible to reduce this to approximately 20%. If it is assumed that all the additional radiation absorbed is available to melt ice, an additional 2 cm of ice per day could thus be melted. The dust does not significantly affect infrared radiation rates, as snow, ice and water react very much as black bodies in the infrared region. Any open water which develops should also hasten melting downstream because the albedo of a water surface is roughly 15%.

"Dusting has been used by the Russians to hasten breakup and to accelerate snow melting, and the energy balance at a melting surface has received a qualitative analysis (Williams and Gold, 1963). At present, however, the analysis is sufficiently vague and experimental results too limited to allow one to predict with any degreee of certainty the effect of a particular dusting operation. At the very least, therefore, the Chena River experiment is a beginning of field tests to indicate the relative feasibility of the dusting technique.

"Plan of operation & results desired

"The plan of operation included dusting of the Chena River for some distance above the mouth and dusting the Tanana River" in portions downriver from the Chena. "It was hoped that results would not only eliminate potential jam points in the Chena, but would provide a receiving area for loose ice from the Chena. In addition, it was felt that if jams should begin to develop in the Tanana, the overflow would move into the flats area to the south rather than into the Fairbanks area.

"... Approximately thirty-five tons of fly ash and coal dust were spread.... Loading ... was accomplished by improvised hopper and crane.... This method of loading was not completely satisfactory and should be improved in future work. The dusting was carried out during the period 12-14 April.... It was not possible to be selective regarding grain size of the material used; however, sieve analyses of samples indicated that more than 70 percent of the fly ash and 40 percent of the coal dust was composed of material smaller than 2mm. D_{10} was typically 0.08mm and the uniformity coefficient, D_{60}/D_{10}, varied from 12 to 60."

"Results of dusting

"On April 16, observations were made along the dusted section of the Tanana and up the Chena. The ice on the Tanana was approximately two feet thick. It, in turn, was covered with approximately 1 1/2 feet of snow, near the Chena Pump Road. This snow thickness gradually tapered off to only a few inches, 1/2 mile upstream on the Chena. The snow where the dust was present was noticeably different in texture from that where the snow was clear. The dusted snow was much wetter and extremely awkward for snowshoeing by the observers. Portions of the ice on the Chena had no snow cover and there the dust had honeycombed the ice to a depth of 4 inches.

"On April 17, twenty-four 5-foot wooden dowels ... were placed on the Tanana in two parallel rows, one row in the dusted snow and the other in clear snow. The dowels went through the snow into holes drilled partially through the ice. The dowels were painted with 6-inch red bands so that readings of snow depths could be taken from shore when conditions did not permit walking on the ice. Every attempt was made to get the conditions at the two rows to be identical except for the presence or absence of dust. This was patently impossible, however. The snow along the dusted row was approximately 12 inches thick and that in the clean section about 23 inches deep. Much of this difference may well have been caused by the action of the dust before the stakes were placed. The dusted and clear snow were vastly different in texture....

"Figure 10 indicates, on a common time scale, the daily range of temperatures recorded in Fairbanks during the course of this experiment. It also shows the total decrease in snow height at the 12 dusty and 12 clean stakes. A reading of 72 inches thus corresponds to an average decrease in snow cover of 72 inches/12 = 6 inches. Finally, it indicates the percentage of the original snow cover remaining, as a function of time, for the two conditions. Statistical tests of the decreases in snow depth for the 24 stakes showed that the probability was negligibly small that the figures in the dusted and white sections came from the same statistical family.

"... On April 27 ... the snow cover was virtually gone in the dusted section and the ice was becoming quite 'rotten'.... Two days later this 'went out.'

"The manner in which the river opened in 1966 is probably the most convincing evidence that the dusting did, in fact, have a significant effect. Rather than the river's randomly opening up more or less as a whole, as it normally does, the dusted channel opened 9 days before the rest of the river.... Moreover the open channel extended only the length of the dusted region.... This one channel was the only significant open water on the Tanana in this region....

"... The warm water from the open channel melted much of the ice in its path. On April 29 and 30, the channel had been open only down to ... where the dust had ended, but ... the sun-warmed water rapidly opened the channel downstream. This process continued rapidly and by May 5, when the Chena was rising rapidly due to the warm temperatures, the lower Chena was completely open and a channel approximately 2 miles long had been opened down the Tanana. This was still the only significant open water in this region of the Tanana. There was no problems with ice jamming at the mouth of the Chena.

"While this experiment was apparently successful, because of its lack of control and because of its specific nature, it cannot be considered conclusive. Certainly, under the particular circumstances encountered, dusting had a significant beneficial effect. It appears worthwhile to repeat this experiment in the same or different locations in future years.... For jam prevention one would normally choose to dust a main channel but such a procedure almost automatically eliminates a great many possibilities for control. A series of dusted strips across the river may be the most practical solution to the control problem. The use of surface vehicles to apply the dust should be considered. In a case such as the one treated where there is a significant snow cover it is possible that a mechanical means for removing the snow may be faster and more economical than dusting from the air.

"One other question arose during the experiment, namely: 'Is it possible for dusting to decrease rather than increase melting rates?' It is commonly known that the layer of dust should not be excessively

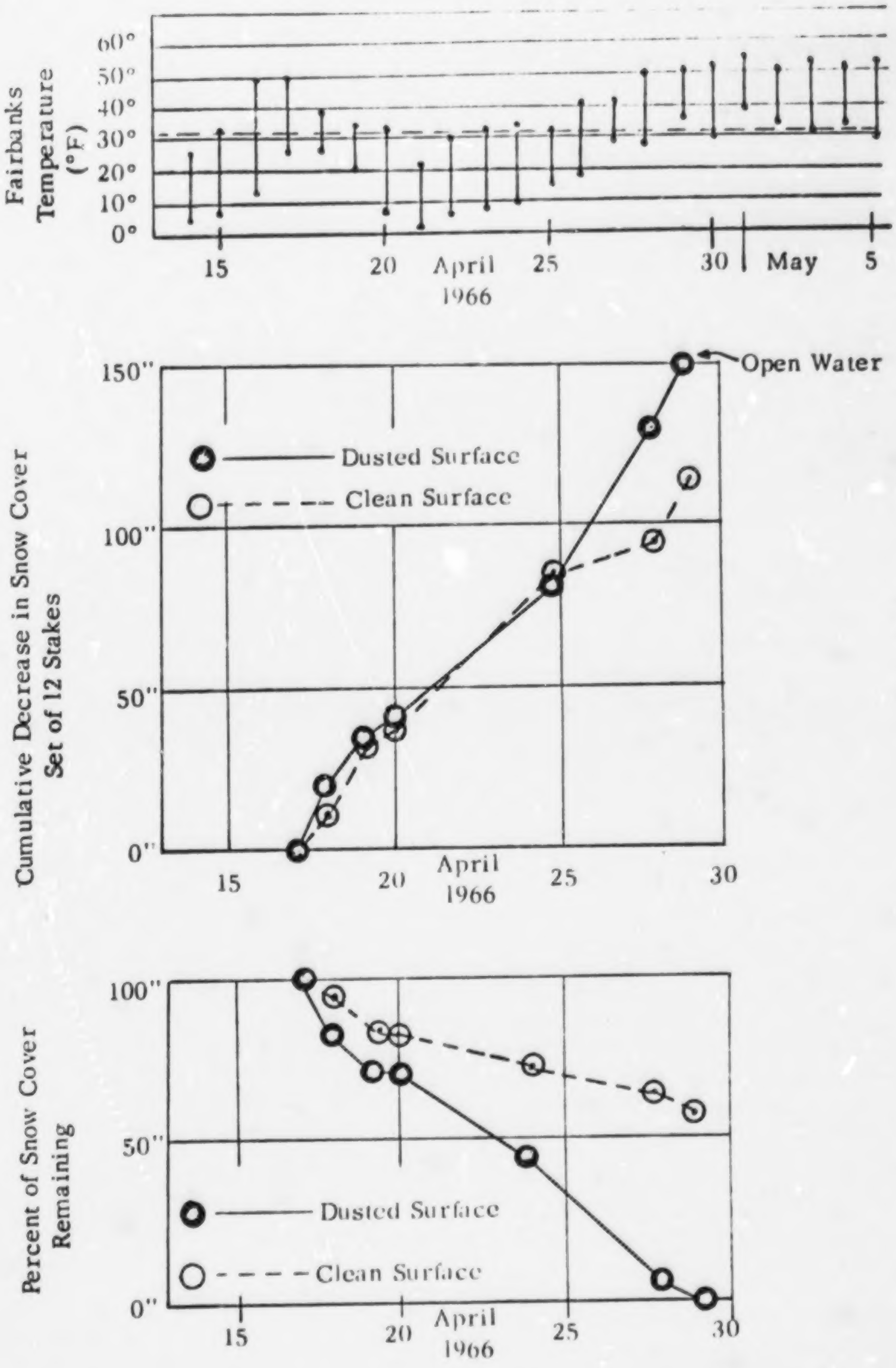


Figure 10 - DAILY TEMPERATURE RANGES AT FAIRBANKS, ALASKA, 1966, AND DECREASE IN SNOW COVER ON DUSTED AND CLEAN SURFACES. (Corps of Engineers, 1967)

thick as it may act as an insulator. The economics of dusting normally keep the layer thin, but it was observed that even quite thin layers can hinder melting by an entirely different mechanism. During the cold snap which occurred during this project, the wet slushy dusted snow froze solidly and appeared to be much slower melting than the untreated snow. This may or may not be a significant problem. On the basis of this limited experience it is impossible to evaluate this variable."

Calcium chloride and coal dust was used in an unsuccessful experiment to break a large ice jam on the Mississippi River (Engineering-News-Record, 1966).

"Helicopters and crop dusting planes spread 28 tons of coal dust and 17 tons of calcium chloride on the ice mass in an attempt to melt through a channel to relieve the flooding. Blasting was ruled out because of the size of the jam. Ice thickness ranged from 18 in. to as deep as 12 ft at one point where it actually froze to the floor of the channel."

"The aerial attack on the ice, although not successful, was a useful experiment.... The calcium chloride melted into the ice up to 12 in. deep. The coal dust, designed to concentrate the sun's heat, only melted about 3 in. into the ice, but its effect was limited because backwash from the helicopter's rotor blew much of the dust away."

The jam was ultimately broken with a towboat.

Granbois (1955) feels that dusting on power plant ponds has only questionable effects.

Dusting on one section of the North Dvina is used only as an aid to icebreakers: (Balanin and Szcherbakova, 1967) "...with the view of the weakening of the strength of ice and increasing the effectiveness of work of ice breakers of small efficiency.

"Some 15-20 days before the ice was to move the blackening of ice and snow-covered areas was being carried out at a distance of 15-20 km in all ice-packed sections of the river. The width of the stripe blackened was 3-5 metres, the quantity of dust materials being about 100 g/m^2 with 0,1 mm dia. particles and less. The blackening speeds up the process of snow thawing and prolongs the period of solar radiation effect on the ice.

"As a result, the thickness of ice cover decreases (approximately 10 cm. as compared to the unpowdered ice) and the top ice (up to 10-20 cm) is demolished....

"Precipitation taking place after the date of steady transfer of average daily air temperature across 0 C in spring makes no influence on the effectiveness of thawing of the ice being blackened.

"Ice thawing is not very intensive in case of the fall of temperature at such periods of time. The degree to which the strength of the ice can be weakened by blackening materials depends on its structure....

"The strewing of chemicals over the blackened ice was carried out from the air not earlier than a few days before debacle of the river (after the ice was free of water); the quantity of chemicals being 100-200 g/sq.m. with the particles dia. up to 0.5 cm."

Antrushin (1961) reports on dusting experiments to prevent jams. Some statements seem to contradict the views of the previous paper.

"The writer, has been able ... to carry out a series of experimental avio-chemical operations on the Northern Dvina and Onega Rivers, in connection with the (artificial) melting of the ice and the acceleration of its (natural) melting. Onto the ice of these rivers we scattered from air craft a total of more than 4000 tons of different blackening substances and chemical preparations. As a result of this work the high spring water levels were successfully prevented at Arkhangel'sk for a period of six years, and navigation on the Northern Dvina began some days earlier. Using the same blackening substances on the ice of the Neman in 1958, we created a channel of length 120 km and width 100 m, which prevented heavy flooding. We note, incidentally, that in the year 1961, in the hope of a warm winter and thin ice, no pre-freshet ice-destroying operations were carried out. The result was that great ice-barrages again formed at the mouth of the river.

"... The most varied blackening substances have been used, and with great effect: ash, foundry loam, dark-colored sands, phosphate fertilizer, and dust collected from earth roads. In selecting them it is necessary to take into account that the most effective are finely dispersed substances having the maximum thermal capacity and thermal conductivity. The ice does not have to be absolutely black, but only dark grey, to lose its strength and break up completely in the pre-freshet current of the river, before the general time of break-up.

"In aerial salting operations we use ordinary salt and mineral fertilizers, potassium salt, calcium chloride and ammonium nitrate. In cases of urgency or schedule-meeting, the ice-blockages may be destroyed by scattering calcium chloride, which is very effective in the first thirty minutes of its action.

"In salting operations, the chemicals are scattered in the form of small lumps of weight from 10 to 80 g, depending on the thickness of the ice. At the points where these lumps fall, holes are formed right through the ice, and thanks to eddy phenomena these holes are converted into polynias, and the treated area of ice acquires a perforated lattice structure. It is characteristic that ammonium nitrate, calcium chloride and potassium salt improve the bottom and water-side flora, and this in turn has a beneficial effect on the fish population.

"On rivers and canals it is expedient not to blacken the ice surface solidly, but to 'carve up' the ice expanses into smaller parts which during the freshet will be freely carried off by the current. In this case we mark out longitudinal strips along the deep-water part of the river bed, and transverse strips perpendicular to the direction of the cold winds. In strips and channels with these directions, a much warmer microclimate is created, with optimum absorption of solar radiation; protection is given against the cold northeast winds. The blackening substances are dusted from a height of 5-10 m, and chemicals are scattered from a height of 10-20 m."

Additional information on these methods are contained in a article in the Aeronautical Engineering Review (1957) and Antrushin (1956).

Dusting with foundry slag after which waste diesel fuel was spread over the surface "to retard evaporation of the poring water" is described.

Barnes (1926) reports on calcium chloride dusting in conjuction with explosives on an ice jam near Franklin, Pennsylvania. Without elaborating he describes the results as "quite effective". Ash, sand and gravel were also used. Ashes spread to a width of 15 yards for a distance of 50 yards made "slush ice by drawing the heat of the sun". Cinders pentrated from ½ to 1 inch in one day. In discussing Barnes' works Ewens (1938) reports: "It is probable that a mixture of calcium chloride with cinders to absorb the sun's heat and prevent too rapid dissolution, would prove the most effective aid to thermit units. It is suggested that the use of such a mixture in concentric circles and radiating lines from the point of placement of each thermit unit, will assist in forming cracks and weakening the ice."

Another report by the Pittsburg District, Corps of Engineers (1960) discusses the work of Barnes and the disadvantages of calcium chloride.

"The use of calcium chloride was also considered as a possible means of attack on the ice jam on the Wabash River in Indiana in February 1959, but was discarded due to the detrimental effect on fish and aquatic life."

Livshits (1961) gives some additional details of Russian ice dusting techniques.

"In order to rapidly melt snow and ice under the influence of solar rays, coal dust or mixture of coal and sand is strewn upon the cover. Large areas can be spread with this by using aircraft. The cost for processing 1 hectare of surface is about 200 roubles, which is approximately 1/10 as expensive as destruction of the ice cover by means of explosives....

"This method can be applied to dealing with small ice jams. Most of this type of jam occurs at bends in meandering rivers. In due time the weakening of the ice cover on these sections will assist the rise and movement of the ice and will ease the passage of the ice from the upper sections of the river."

In a short article, (Engineering News-Record, 1959) a dusting method using sand is described.

"The Russians have been using aircraft equipped with sand sprayers to break up ice jams in Siberian rivers.

"The planes sprayed waste sand from metal molding shops to turn the ice black.... As sand grains melted the ice, they formed minute tunnels that filled with water. At night the water froze, expanding in volume and bursting the surrounding ice.

"One river was reported open for shipping 10 to 12 days earlier than usual after this method was used."

Laktionoff (1957) discusses methods of dusting to combat ice jams in Russia. It should be noted that the ice albedo measurements mentioned in his paper are possible for snow (Gerdel and Diamond, 1956; and Bolsenga, 1964) but seem somewhat high for ice. Some unreported ice albedo measurements on Lake Superior at solar altitudes from 30 to 40° varied from 10% for clear ice to about 70% for partially snow covered ice. A summary of Laktionoff's description is given below.

"Much better in this respect are investigated the radiating properties of the ice cover. N. T. Chernigovsky, G. N. Yakovlev, N. N. Andreeva, I. G. Petrov and others by using modern methods of actinometry, have established that the ice and snow surface had a great reflectivity reaching 90 to 95 percent of the incident radiation, and that owing to high transparency of the atmosphere and to very long day the flow of the sun radiation reaching the ice even in Arctic was very important. At the same time, substances were determined both by theoretical and practical way, which are most effective in lowering albedo and retaining the sun radiation heat.

"On the basis of these investigations I. S. Peschansky, N. T. Chernigovsky, G. N. Jakovley, I. G. Petrov and others have developed a well scientifically supported radiation method of accelerating the ice thawing over great surfaces.... This has proved to be a rather effective means of acting upon the ice for navigation purposes and has allowed to lengthen the navigation in some harbours...."

The remainder of the paper describes dusting experiments of Konovalov and Miasnikov. Their original paper is translated below.

Konovalov and Miasnikov (1956) emphasize that dusting is better suited for ice jam prevention rather than removal even under most favorable conditions.

"In the spring of 1955, following an agreement with the Waterways Administration of LIIVT (Leningrad Institude of Water Transport Engineers), experiments were made on darkening ten chosen sections of the snow-ice cover (each sections having dimensions of 40 x 30 m) in the Rybinskyj reservoir. The sections were dusted with various materials and various doses.

Sections 1 and 2 were covered with a fine coal dust, the particles having a diameter of 0.2-1 mm. using 12 and 20 g., respectively, on 1 m^2.

Sections 3, 4, and 10 were covered with coal powder mixed with river sand in the following order:
a) 100 g. coal with 100 g. sand
b) 150 g. coal with 150 g. sand
c) 200 g. coal with 200 g. sand for 1 m^2.

Sections 5, 6, 7, and 8 were covered with coal powder, the particles having diameters 0.2-5 mm. using 100, 200, 300, 400 g. respectively, for 1 m^2.

Section 9 was covered with coal slag with particle diameter size 2-10 mm. using 400 g. for 1 m^2.

"In the Irtysh River, on the N.-Krasnoyarsk sandbar the snow-ice cover was darkened with coal slag having a diameter of 0.2-1 mm. Working in community with LIIVT, the Irtysh B.U.P. in 1955 carried out experiments in the Pavlodarskyj back-waters. The substances used there were coal, slag, and soot. These were dispersed in the Rybinskyj reservoir and the Pavolodarskyj back-waters by hand, and in N. -Krasnoyarsk sandbar by airplane.

"The 1955 endeavors have not yet provided enough materials to permit theoretical calculation of the heat balance in ice-snow melting and of acceleration of the breakup period on rivers and reservoirs, however, they have facilitated experiments on the effectiveness of covering the snow-covered ice sheets with dark powdery substances.

"The results of meteorological and actinometric observations on the various sections of the Rybinskyj reservoir indicated that on the dusted sections the average heat balance for snow-ice melting was increased 2.22 times, and on some sections, such as section 8, even 2.52 times....

"The melting of snow, disregarding the effect of snowstorms and rains (which decrease the comparative effectiveness of the radiation balance), progressed more rapidly on the dusted stretches than on the natural ones, on the average 2.39 times, and on some sections (2nd and 3rd) 3.5 times.

"For the period from April 10 to May 1, the melting of ice on the darkened sections amounted to 67.5 cm, whereas in the same span of time, on the natural stretches, the melting amounted only to 39 cm; that is, the melting of ice here proceeded 1.74 times more slowly than on the darkened sections and 1.93 times more slowly than on sections 4, 8, 9, and 10. If we deduct the melting of ice from below, then melting from above on the dusted sections proceeded twice as fast.

"On some days, melting on the dusted sections proceeded with a speed of 7.3 cm per day (24 hrs.) while on the same days on the natural stretches, it did not exceed 3-3.5 cm in a day.

"By May 1, 30-60% of the ice area was completely melted on the dusted sections, while the remaining ice was severely broken-up and on the verge of disintegration. At this time, on the natural stretches, and on the remainder of the reservoir, complete freeze-up still existed....

"Overlooking the fact that the icebreaker 'Don' began working in the reservoir on May 1, the first vessels followed it on May 5-6, and normal navigation began May 11-12 (on May 9, according to aerial surveillance up to 40% of the reservoir was still covered by ice). The ice was cleared 8-10 days earlier on the dusted stretches than on the natural ones, overlooking that meteorological conditions for that year and conditions on the reservoir, in regard to number of solar days, are less favorable than in the eastern, southern, and central basins of the SSSR.

"On the Irtysh River, a portion of the N.-Krasnoyarsk sandbar was dusted from the air. Here, ice jams formed annually, obstructing navigation and damaging the national economy.

"The dusting was done on April 3 from an AN-2 airplane, having a hopper with a capacity up to 1000 kg. and a special devise for dusting. Because of high shores on the sandbar and considerable transverse winds, the fine slag was carried out of the selected folds, and one section of the stretch had to be dusted by hand.

"Refueling for slag powder was done in Omsk.... The cost of the process was 850 rubles for the flight-time and for a very large area, the cost of one-night dusting was -14-15 rubles for an area of 1 hectare.

"In the stretches dusted with slag, the snow melted 10-18 times more rapidly than in the natural stretches, and melted 8 days earlier than the undusted stretch; melting of snow proceeded in the course of 2 days when average daily temperatures were minus 5-5.8° C. (minimum temperatures at this time reached minus 11-12°).

"Intensity of ice melting on the dusted sections was 3.32 - 4 times faster than on the natural ones (Diagram 5) ... There was no ice jam on the sandbar. This speaks about the effectiveness of the conducted works.

"The works conducted by the Irtysh B.U.P. in the Pavlodarskyj back-waters in 1955, where slag and coal were strewn around wintering ships, gave positive results. The work of ice-breakers around the vessels was reduced here, and for some vessels, was not needed at all."

"Darkening of the snow-ice cover ... has an important significance in combating ice jams. An overwhelming majority of ice jams re-occur in their habitual locations and in places where, in the winter, ice floes form in sharp bends of the river. The ice floes, being wider than the lower-lying stretches, and meeting them at considerable angles, are not able to advance during low horizons, and produce a basis for spring ice jams.

"By creating conditions of intense melting on some of the stretches, and dividing the principal floes into a series of sections, or even severely weakening the durability of the ice by means of dusting with slag or coal, it is possible to create a passage way for all of the floes to float downstream simultaneously with the upper and lower-lying stretches. The cost of the work can be reduced considerably by dusting, not the entire area of the presupposed jam extent, but only individual strips, each having widths of 3-6 m.

"The carried-out experiments allow us to make preliminary assumptions on the norms of dusting, methods and time required for executing the work, and the most effective materials.

"In the sections dusted with slag and coal powder, on the Rybinskyj reservoir, snow melts 2.34 - 3.5 times faster than on the natural stretches, and 10-18 times faster on the N.-Krasnoyarsk sandbar of the Irtysh River: Taking into account the fact that snow melting on the Rybinskyj reservoir, to a great degree, was promoted by rainfall, and that results are not typical for all the stretches, it is necessary to consider only the most implicative data obtained on the Irtysh R. An average approximation of increase of melting can be accepted to be in the range of 6 - 10.75 times. The most rapid melting of snow resulted from the fine slag powder and coal powder with particle dimension of 0.2-1 mm.

"The intensity of ice melting on the stretches dusted with slag, coal, coal with sand, and soot, when compared to the natural stretches, exceeds them 1.74 - 1.93 times on the Rybinskyj reservoir and 3-4 times on the N.-Krasnoyarsk sandbar."

The Rybinskyj reservoir compared with the Irtysh River, has less favorable solar radiation, and for this reason, the average between them, that is, the intensity of melting is 2.37 - 2.97 times more rapid than on the natural stretches. The most intensive ice melting was implemented by coal slag having particle diameter 0.2-1.5 mm using 0.4 kg. for 1 m^2, and coal powder with diameter 0.2-3 mm. with a norm of 0.3 - 0.4 kg. for 1 m^2.

"Melting was good on the 4th and 10th sections where a mixture of sand and coal was used in the proportions 150 g. sand with 150 g. coal and 200 g. sand with 200 g. coal powder. On the Rybinskyj reservoir, the difference of melting between the 4th and 10th sections as opposed to the 9th and 8th sections was not more than 8%.

"Not bad results were obtained on the 1st and 2nd sections dusted with fine coal and coke powder using 12-20 g. of the powder for 1 m^2. (80% of the particles had a diameter form 0.2 to 1 mm.).

"Considering that with the first rays of sunshine, a small fraction of the slag and coal would produce some melting and enter into the ice, and thus be protected from blowing away, it is expedient to dust the ice with fine particles (0.2-0.5 mm.) and not exceeding, in any event, 1 mm. The amount used for dusting can be cut down to 50-100 g/1 m^2 without damaging the effectiveness, and this way, costs can be cut down 4-6 times.

"Small fractions of coal and slag possessing crystalline structure, are sustained by snow or ice fairly well. Sinking rapidly into the mesh they created, the grains resist removal by water currents or by the agitated layers of water on top of the ice during melting. If this were so, then the particles of slag and coal would be shifted around on the surface, and would accumulate in some places; leaving other places bare; this is exactly what happened in the case of dusting with soot. Nevertheless, even in giving preference to the finer fractions, these must be dusted on a clear sunny day (particularly from an airplane). The grains of slag, coal, and sand, under the influence of the sun, melt 'cells' for themselves very rapidly, and become inlodged in the ice.

"Satisfactory results were obtained on the sections dusted with a mixture of coal powder and fine sand. In those places where sufficient amounts of slag are lacking, it is recommended to dust the snow-ice cover with a mixture of coal and sand in proportions from 50 g. of fine coal with 50 g. of fine sand, to 100 g. coal with 100 g. sand.

"In the spring of 1955, because of strong winds and snowstorms, the dusting period was stretched to 10 days; this, however, was barely reflected in the work because the sections that were dusted earlier were covered by the snow, and began melting almost at the same time as those dusted later. If we consider that on the sections dusted earlier (in view of the increase of roughness) snow was swept in by winds from neighboring stretches, then apparently, the earlier periods of dusting (40-50 prior to clearing of waterways) are not justified.

"It is most expedient to do the dusting 30-35 days prior to the opening of the river and waterways. In the northern and arctic basins, where the sun begins to warm-up the area earlier; dusting can be started 50 days prior to the breakup; in certain years, however, it may be necessary to renew the dusting of these sections 30-35 days before breakup with a few norms of small fraction dispersal, in order to produce a more pronounced melting in the selected sections that were covered by snow after the original dusting. A second dispersal, then, is expedient in those regions where a substantial amount of snow falls during the final term, and where frequent snowstorms occur, because, due to its reflective property (80-95%), the thickness of a layer of pure snow can prolong the melting considerably.

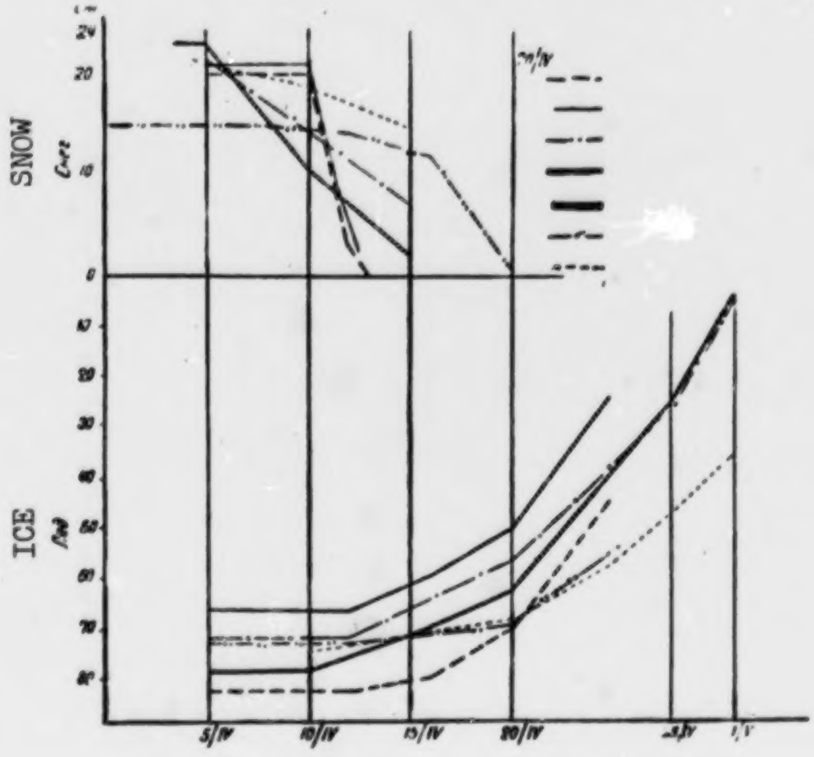
"The result of dusting will be all the more effective with a greater amount of time of sunshine in the region during the two months prior to ice drift. From this, the conclusion can be drawn that, in choosing the location for dusting, it is necessary to know the number of days and hours of sunshine in the two months preceding ice drift, since direct solar radiation produces the most effective melting. Where there is little sunshine, the results are not very satisfactory."

Bezuglov (1959) mentions dusting procedures on the Neman River and emphasizes that satisfactory results depend on favorable insolation conditions.

Diagram 5. The graphic intensity of ice and snow melting on the Rybinskyj Reservoir and on the Irtysh River (April, 1955). From April 20-25, ice thickness on the N.-Krasnoyarsk "sandbar" was obtained by approximation. (Konovalov and Miasnikov, 1956)

Designated Conditions:

— — —	ice and snow on the 1st and 2nd sections of the N.-Krasnoyarsk "sandbar"
———	ice and snow of section 2 of the Krasnoyarsk "sandbar"
— ··—	ice and snow on the natural stretches of the "sandbar"
———	snow of sections 2 and 3 on the Razhnovskoj Cape of the Rybinskyj Reservoir
———	ice of sections 8, 9, and 10 on the Cape
— · —	snow and ice (average) on the 10 darkened sections on the Cape.
---------	snow and ice on the 5 natural stretches of the Cape.



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Thermal regime modification

Thermal regime modification or thermal pollution is used here to mean that river water temperatures are artificially altered to prevent the formation of river ice. Alteration is most commonly effected by power plant, sewage, and industrial discharge.

Similar to dusting, thermal modification is not used to remove ice jams. However, the large ice modification effects automatically classify this method as a possible ice jam prevention measure.

Dingman, Weeks, and Yen (1967) analyze the effects of the thermal pollution on river ice.

"Pruden et al. (1954) studied the heat balance of the St. Lawrence River in an attempt to determine the feasibility of keeping much of the river ice-free for parts of the winter.... Because plots of the heat loss rate ($Q*$) vs air temperature (T_a) and vs water temperature (T_W) were close to linear (using average monthly values for meteorologic conditions), they wrote

$$Q* = 183.6 + 15.5\, T_a + 43.1\, (T_w - T_a) \qquad (1)$$

where $Q*$ is in cal cm^{-2} day^{-1} and T_w and T_a are in degrees C. This expression for $Q*$ was then incorporated in a differential equation for cooling rate with distance, which is similar to the one derived in this paper. The inverse of their expression for $Q*$ can be integrated in closed form, and they found a simple exponential decrease of water temperature with distance which is very similar to that found in the present paper.... Their approach is, however, less satisfactory, as their expression for $Q*$ was developed for monthly average values at one general location only, and does not take into account the many meteorologic variables which affect the heat loss rate....

"Ince and Ashe (1964) used observations from the St. Lawrence River to compare two methods of calculating downstream water temperature decreases. Both of these are based on a finite difference approach for a parcel of water moving at the average velocity of the river:

$$T_{w_2} - T_{w_1} = \frac{Q t}{D \rho_w C_p} \qquad (2)$$

where $Q\uparrow$ is heat-loss rate (cal sec^{-1}), D is river discharge (cm^{3}sec^{-1}), ρ_w is mass density of water (g cm^{-3}), C_p is specific heat of water (cal g^{-1} °C^{-1}), and $(T_{w_2} - T_{w_1})$ is temperature change of the water parcel over some time period (°C)....

"While the basic approaches of these earlier studies are sound, and led to some success in river temperature prediction, they are all limited in some respect. The principal limitations lie in the formation of the expressions for heat loss rate ...."

"Basic equation

"The differential equation for downstream changes in water temperatrue under certain simplifying assumptions is developed as follows. Referring to Figure 1, consider a stream, carrying a steady flow, whose geometry is constant in space and time. Assume further that meteorological conditions above the stream are spatially and temporally constant. If water temperature changes in the downstream (x) direction only, the amount of heat advected into volume element w·h·dx in unit time, Q_1 (cal sec^{-1}), is

$$Q_1 = \rho_w v_w h w C_p (T_w - T_{nat}). \tag{4}$$

The heat transfer to the volume by conduction, Q_2 , is

$$Q_2 = -khw \frac{dT_w}{dx}. \tag{5}$$

Here ρ_w is the mass density of the water (g cm^{-3}), is the flow velocity of the water (cm sec^{-1}), h is the flow depth (cm), w is the stream width (cm), C_p is the specific heat of the water (cal g^{-1}·K^{-1}), considered constant in the temperature range T_w to T_{nat}, T_w is the water temperature (°K), k is the eddy thermal conductivity of the water (cal cm^{-1} sec^{-1}·K^{-1}), and T_{nat} is the natural water temperature just upstream from the thermal pollution site (°K). The amount of heat advected from this volume is

$$Q_3 = \rho_w v_w h w C_p \left[(T_w - T_{nat}) + \frac{dT_w}{dx} dx \right] \tag{6}$$

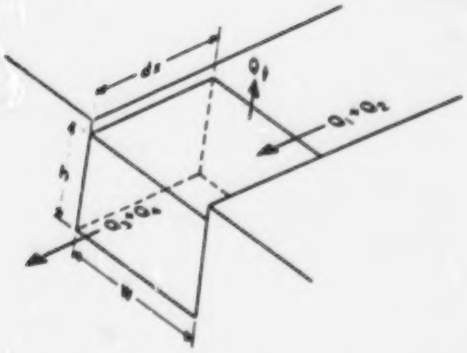
dx
Q1
Q1+Q2
h
Q3+Q4
w

Fig. 1. Definition sketch for basic equation. (Dingham, Weeks, Yen, 1967)

and that leaving by conduction is

$$Q_4 = -khw\left[\frac{dT_w}{dx} + \frac{d^2 T_w}{dx^2}dx\right]. \tag{7}$$

The water surface acts as a heat sink, and the total heat lost from it, $Q\uparrow$, is

$$Q\uparrow = Q^{*} \cdot w \cdot dx, \tag{8}$$

where Q^{*} is the heat loss rate per cm^2 of water surface. A heat balance statement for the volume of water may be written as

$$Q_1 + Q_2 = Q_3 + Q_4 + Q\uparrow, \tag{9}$$

which reduces to

$$Q^{*} = -\rho_w v_w h C_p \frac{dT_w}{dx} + kh\frac{d^2 T_w}{dx^2}. \tag{10}$$

Neglecting the second order (conduction) term, eq 10 simplifies to

$$x = -\rho_w v_w h C_p \int_{T_i}^{T_x} \frac{dT_w}{Q^{*}}, \tag{11}$$

where

$$T_i = T_{nat} + \frac{Q_P}{\rho_w v_w h w C_p},$$

$$T_x = \text{water temperature at } x. \tag{12}$$

"T_{nat} is the natural water temperature just upstream from the thermal pollution site, and Q_p is the heat of pollution (cal sec^{-1}). By evaluation eq 11 at different values of T_x, the cooling curve downstream from the thermal pollution site can be obtained.

"Before examining $Q*$ further, the assumptions involved in the derivation of eq 11 should be considered. In most cases, the assumption of steady flow is reasonably good for ice-covered rivers, and, unless large tributaries enter, discharge can be considered nearly constant over fairly long reaches. Where large tributaries are present, or where there are significant changes in stream geometry along the reach of interest, the total reach can be subdivided and each subreach considered separately. A similar approach could be used to consider spatially varying meteorologic conditions.

"The assumption that water temperature is constant throughout any cross section of the river is more difficult to evaluate. The intensity of turbulent mixing in a given direction equals the product of the coefficient of turbulent diffusion and the velocity gradient in that direction. Thus vertical mixing tends to be more complete (and hence temperatures more uniform vertically) in a shallow, fast stream than in a deep, slow one. By the same reasoning, one would expect narrow, fast streams to have more complete lateral mixing and more uniform temperature horizontally than wide, slow streams. Sayre and Chamberlain (1964) found that the coefficient of lateral turbulent diffusion is approximately proportional to the 3/2 power of the mean flow depth, so that one may add that, velocity gradients and other things equal, greater depth of flow promotes lateral mixing.

"If there is a basis for estimating the lateral temperature gradient at various points along the reach of interest, consecutive subreaches of varying width can be used to approximate the natural conditions. Where no such information exists, one must be satisfied with the assumption of complete isothermality in all cross sections. For an example of how erroneous this assumption can be, see Mackay (1966).

"Evaluation of $Q*$

"To solve eq 11, the heat transferred from the water to the air must be written as a funcion of water temperature T_w. To do this, a second heat balance equation is written in which all the modes by which heat can enter and leave the volume of water w·h·dx, aside from advection, are enumerated. The magnitude of the heat transferred by each mode is written as a function of hydrometric and meteorological variables, and the sum of these equated to $Q*$. As shown below, the terms which contribute singificantly to $Q*$ can be evaluated under given climatic and flow conditions.

"Q^* can thus be written as

$$Q^* = Q_R - Q_B - Q_E - Q_H - Q_S + Q_G + Q_{GW} + Q_F \qquad (13)$$

where

Q_R is heat added at the river surface as short-wave radiation;

Q_B is net loss of heat by the exchange of long-wave radiation with the atmosphere;

Q_E is heat loss due to evaporation;

Q_H is sensible heat lost by conduction and subsequent convection from the water to the atmosphere;

Q_S is heat lost as a result of snow falling into the water;

Q_G is heat added by the flow of geothermal heat through the stream bed;

Q_{GW} is heat added by the flow of ground water into the stream through its bed and banks;

Q_F is heat increase due to fluid friction.

With these definitions, Q^* is negative when there is a net loss from the volume w·h·dx.

" Q_R

"Direct measurements of solar and atmospheric short-wave radiation at the site under consideration are obviously best for determining the magnitude of the energy supplied by this means. Where these do not exist, measurements from stations at some distance from the site can be substituted, provided there is reason to believe that the cloud cover conditions at the two sites are comparable during the period of concern. If direct measurements of short-wave radiation are lacking, estimates of its magnitude can be made by using tables, graphs, or formulas relating percentage of possible sunshine or cloud cover to the percent of possible solar radiation which reaches the ground (see, for example, List, 1963, Tables 151, 152; Anderson, 1954, p. 74-77; Jensen and Haise, 1963, App. I). Bolsenga (1964) has provided tables of daily sums of cloudless sky short-wave radiation for various latitudes and air mass conditions which can be used as a basis for such estimates. For the purposes of the present paper, the amount of incident short-wave radiation Q_{RI} is estimated using the relation initially suggested by Angstrom (List, 1963):

$$Q_{RI} = Q_{CL}\,[0.35 + 0.061\,(10 - C)] \tag{14}$$

where Q_{CL} is the incoming short-wave radiation for a cloudless sky and C is the cloudiness expressed in tenths (i.e., with complete cloud cover, C = 10).

"A portion of the short-wave radiation which reaches the water surface is reflected, and this must be subtracted from the incident radiation to find the energy actually absorbed.... Koberg (1964) has suggested...plotting curves for reflected short-wave radiation versus measured short-wave radiation for both clear and cloudy skies. In the present paper the amount of reflected short-wave radiation Q_{RR} was estimated by fitting a polynomial to average values between Koberg's clear and cloudy sky curves:

$$Q_{RR} = 0.108\,Q_{RI} - 6.766 \times 10^{-5}\,Q_{RI}^2\,. \tag{15}$$

Koberg estimates that this should be accurate to within 10%. The amount of energy absorbed by the water is then calculated by

$$Q_R = Q_{RI} - Q_{RR}. \tag{16}$$

"Under conditions where T_w T_a, and windspeed is low, fog generally occurs. Such conditions are more likely the greater the difference $(T_w - T_a)$ becomes. Q_R, therefore, is commonly appreciably less than Q_{CL} and contributes only slightly to the total energy budget.

"Q_B

"The net heat lost from the water surface as long-wave radiation is given by

$$-Q_B = Q_a - Q_{ar} - Q_{bs} \tag{17}$$

where Q_a is the incoming long-wave atmospheric radiation, Q_{ar} is the reflected long-wave atmospheric radiation, and Q_{bs} is the back radiation from the water surface. The Lake Hefner studies (Anderson, 1954, p. 96-98) have established that the emissivity of water is 0.970 and is independent of the temperature and concentration of dissolved solids. Thus

$$Q_{bs} = 0.970\,\sigma T_w^4, \tag{18}$$

where σ is the Stefan-Boltzmann constant (1.171×10^{-7} cal cm^{-2} day^{-1} °K^{-4}) and T_W is water temperature in °K.

"Where Q_a is not measured, it can be related empirically to air temperature, vapor pressure, and cloud conditions (Anderson, 1954, p. 88-98). For clear skies the relation initially suggested by Brunt is used with the empirical constants determined by Anderson:

$$Q_a = (0.68 + 0.036\sqrt{e_a})\,\sigma T_a^4 \tag{19}$$

where T_a is the air temperature in °K, e_a is the vapor pressure of the air in mb, and Q_a is expressed in cal cm^{-2} day^{-1}. For cloudy skies Q_a was estimated by

$$Q_a = (a + be_a)\,\sigma T_a^4 \tag{20}$$

where

$$a = 0.740 + 0.025\ C \exp\ (-1.92)(10^{-4})H \tag{21}$$

$$b = (4.9)(10^{-3}) - (5.4)(10^{-4})\ C \exp\ (-1.97)(10^{-4})H \tag{22}$$

and

$$500 \leq H < \infty.$$

Here C is the cloudiness expressed in tenths and H is the cloud height in meters. For cloud heights less than 500 m, the cloud height is taken as a constant at 500 m (Anderson, 1954). Because the emissivity of water is 0.970, its long-wave reflectivity is 0.03, so that $Q_{ar} = 0.03\ Q_a$.

"If weather observations are available, the value of e_a can be computed from

$$e_a = \frac{U\ e_{sa}}{100} \qquad (23)$$

where U is the relative humidity and e_{sa} is the saturation vapor pressure of the air at temperature T_a. The value of e_{sa}, which is a function of temperature alone, can be calculated with the Goff-Gratch formaula (List, 1963, p. 350).

" $Q_E + Q_H$

"In studies of this type, $Q_E + Q_H$ is generally estimated by using an empirical formula to calculate either Q_E or Q_H and then using the Bowen ratio

$$R = \frac{Q_H}{Q_E} \qquad (24)$$

to find the other. The value of R is calculated from

$$R = (6.1)(10^{-4})\ P\left[\frac{T_w - T_a}{e_{sw} - e_a}\right] \qquad (25)$$

where P is atmospheric pressure (mb), e_{sw} is saturation vapor pressure at the temperature of the water (mb), e_a is vapor pressure of the air (mb), and other symbols are as previously defined.

"Equation 25 is derived on the assumption that the eddy diffusivities of water vapor (κ_w) and heat (κ_h) in air are equal. Examination of previous literature reveals uncertainty about the conditions under which this assumption holds true. Pasquill (1949), Veihmeyer (1964) and Fritschen (1965) all reported satisfactory results using eq 25 when atmospheric conditions are neutral or stable. Anderson (1954, p. 117) also concluded as a result of the Lake Hefner studies that little error appears to be introduced in the estimates as the result of neglecting the effects of atmospheric stability. Brutsaert (1965, p. 13) cites one report in which $\kappa = \kappa_h/\kappa_w$ was found equal to unity regardless of atmospheric stability, and another where the ratio was found equal to unity *except* under highly stable conditions, where it increased to 2 or 3. In unstable conditions ($T_w >> T_a$), Pasquill (1949) reported that κ could be as large as 3. A similar increase in the value of κ with an increase in ($T_w - T_a$) was noted by Roll (1965, Fig. 81). However, Rimsha and Donchenko (1957), whose work is discussed more fully below, successfully used the Bowen ratio with $\kappa = 1$ to calculate wintertime heat losses from calorimeters and open river reaches, with ($T_w - T_a$) as great as 30 C. In view of these latter studies, it seems reasonable to use the Bowen ratio in calculating Q_E and Q_H under the conditions of interest here. Since κ enters the theoretical derivation of R as a product term, the lack of information as to its true value can introduce considerable uncertainty in the estimates of Q_H or Q_E and hence in the total heat loss rate. The possibilities of such error must be kept in mind in situations such as discussed herein.

"Using the Bowen ratio, two approaches to calculating Q_E and Q_H were attempted. The first involves using a simple, well accepted formula for calculating daily evaporation rates (Kohler, 1954).

$$E = [(0.525)(10^{-2}) + (1.007)(10^{-2})\, v_a]\,(e_{sw} - e_a) \tag{26}$$

where E is evaporation rate (cm day^{-1}), v_a is average wind velocity at the 4-m level (m sec^{-1}), e_{sw} is saturation vapor pressure at the temperature of the water surface (mb), and e_a is the vapor pressure of the air at the 2-m level (mb). Multiplication of eq 26 by suitable constants allows the heat lost as a result of evaporation to be calculated by

$$Q_E = (3.135 + 6.011\, v_a)(e_{sw} - e_a) \tag{27}$$

where Q_E is in cal cm^{-2} day^{-1}, v_a is in m sec^{-1}, and e_{sw} and e_a are in mb. Assuming that eq 27 is applicable within small limits of error when 2-m wind velocities are used, and that P = 1000 mb, its multiplication by eq 25 yields*

$$Q_H = (1.91 + 3.67 v_a)(T_w - T_a). \tag{28}$$

---

* If changes are made in eq 26, 27, and 28 to correct for the substitution of average wind velocities determined at the 2-m level in equations based on 4-m wind velocities, these equations change to

$$(0.525)(10^{-2}) + (1.229)(10^{-2})\, v_a \;\; (e_{sw} - e_a) \tag{26a}$$

$$(3.135 + 7.33 v_a)(e_{sw} - e_a) \tag{27a}$$

and

$$(1.91 + 4.47 v_a)(T_w - T_a). \tag{28a}$$

"The second approach uses the equations developed by Rimsha and Donchenko (1957), who assumed that Q_H could be calculated by a relation of the form of eq 28, and determined the wind function parameters by least squares analyses of data from calorimeters exposed adjacent to natural ice-free reaches. The principal difference in the two approached lies in the fact that the "constant" in the wind function was found by Rimsha and Donchenko to vary with $(T_w - T_a)$. Thus, after adjustment for application to natural reaches (based on actual comparison of heat losses from rivers and calorimeters), they wrote

$$Q_H = (k_n + 3.9 v_a)(T_w - T_a) \tag{29}$$

where v_a is 2-m windspeed in m sec^{-1} and k_n is empirically found to be

$$k_n = 8.0 + 0.35(T_w - T_a). \tag{30}$$

The parameter k_n thus represents the portion of heat transfer due to free convection. The Bowen ratio, assuming P = 1000 mb, was then applied by Rimsha and Donchenko (1957) to eq 29 to give

$$Q_E = (1.56\,k_n + 6.08\,v_a)(e_{sw} - e_a). \tag{31}$$

It is interesting to note that the wind coefficient in eq 31 is very close to that found by Kohler (1954, eq 27). Thus eq 27 is a special case of eq 31, which is, according to eq 30, appropriate for $(T_w - T_a) < 1C$.

"Figure 2 compares $Q_H + Q_E$ as calaculated by eq 27 and 28 with that calculated by eq 29 and 31, and illustrates the large differences which arise from introduction of a term accounting for natural convection. The differences are, as expected, most pronounced at low windspeeds.

"It is recognized that eq 26-31 are simplifications, and that the constants in each actually depend upon such factors as wind sheltering, fetch lengths, and the amplitude and frequency of wind variations at the sites for which they were determined. Some field tests are described below, but many more are needed before the general applicability of one or the other set of equations is demonstrated.

"Figure 3 shows the relative importance of Q_B, Q_E and Q_H under differing meteorological conditions using eq 29, 30 and 31.

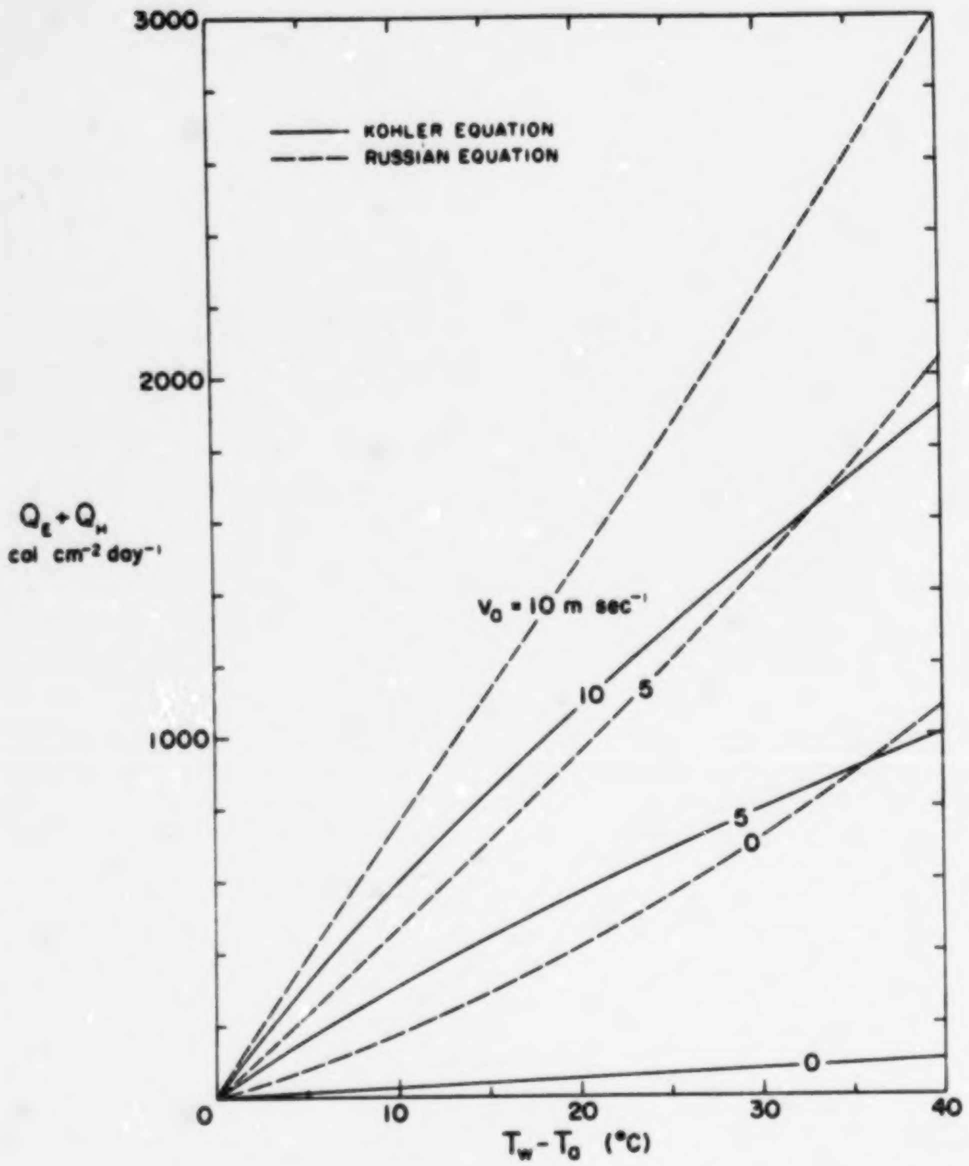

Fig. 2. $(Q_E + Q_H)$ vs $(T_W - T_a)$ at v_a = 0, 5, and 10 m sec^{-1}, U = 100%. The different curves are calculated by the Russian winter equation and by the Kohler equation method.

(Dingham, Weeks, Yen , 1967)

" Q_S

"The heat lost as a result of snow falling into the water Q_S(cal cm^{-2} day^{-1}) can be estimated by using the relation

$$Q_S = A[L + C_i(T_w - T_a)] \tag{32}$$

where A is the snow accumulation rate (g cm^{-2} day^{-1}), L is the latent heat of fusion of ice (cal g^{-1}), and C_i is the heat capacity of ice. If possible, A should be taken from direct measurements of snowfall rate. In many cases these do not exist, but estimates of visibility will be available, and a satisfactory estimate may be possible using a relationship such as that suggested by Mellor (1966):

$$A = 7.85V^{-2.375} \tag{33}$$

where V is visibility in km. Equation 33 was found to hold reasonably well over the range $1 \leq V \leq 10$ under calm conditions. A feel for the relative importance of Q_S in contributing to the value of Q^* can be obtained by comparing Figure 4 with Figure 3."

With sufficient data, it is possible to calculate Q_G, Q_{GW} and Q_F. However, these factors are considered negligible in most cases and are not included here.

"Calculation of X

"The distance downstream from the site of thermal pollution to the cross-section at which the water temperature has decreased to a given value is found by substituting the chosen expressions for the heat budget components (eq 14-34) in eq 11 and integrating between suitable limits. It is clear that if the meteorological parameters T_a, v_a, e_a, , V, C, H and P can be considered as known constants over the reach of a river of interest, is a function of water temperature only. Unfortunately, the function

$$\int dT_w/Q^*$$

cannot be integrated in closed form and numerical integration must be used.

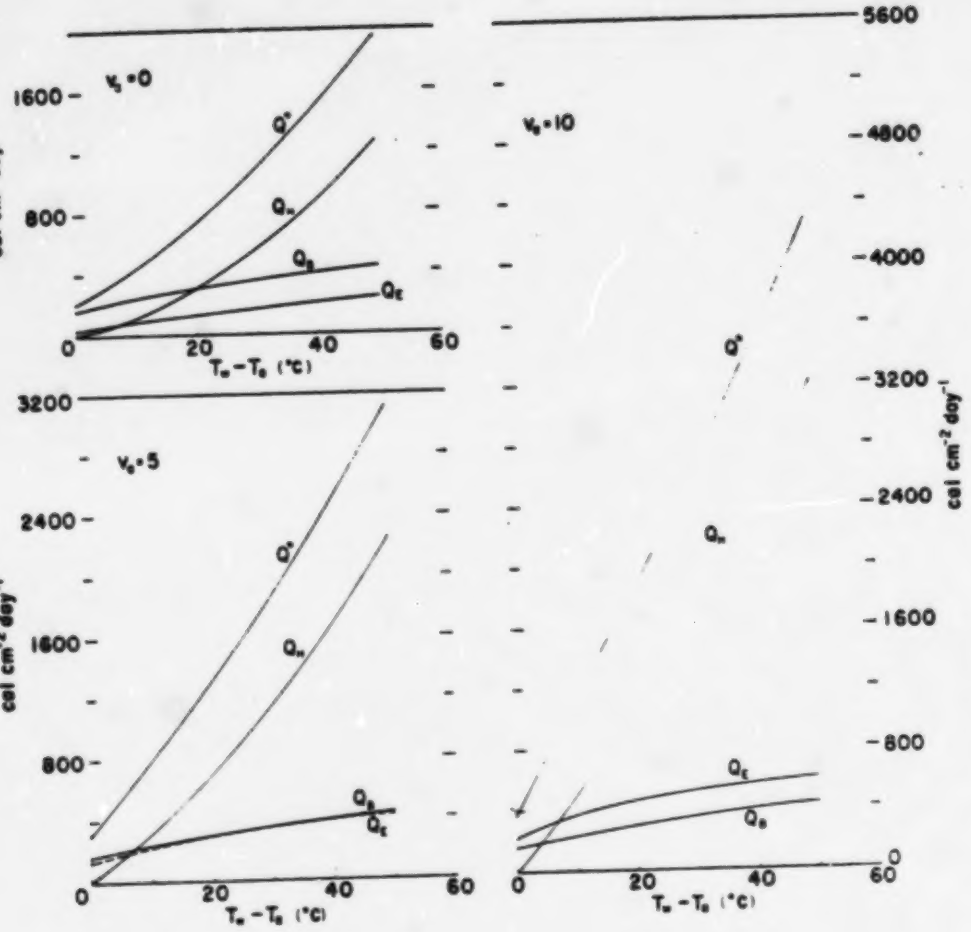

Fig. 3. Q_B, Q_E, Q_H, and Q^* vs $(T_W - T_a)$ at $v_a = 0$, 5, and 10 m sec-1; U = 50%; clear-sky conditions. Q_E and Q_H calculated by the Russian winter equation and Bowen ratio. (Dingham, Weeks, Yen , 1967)

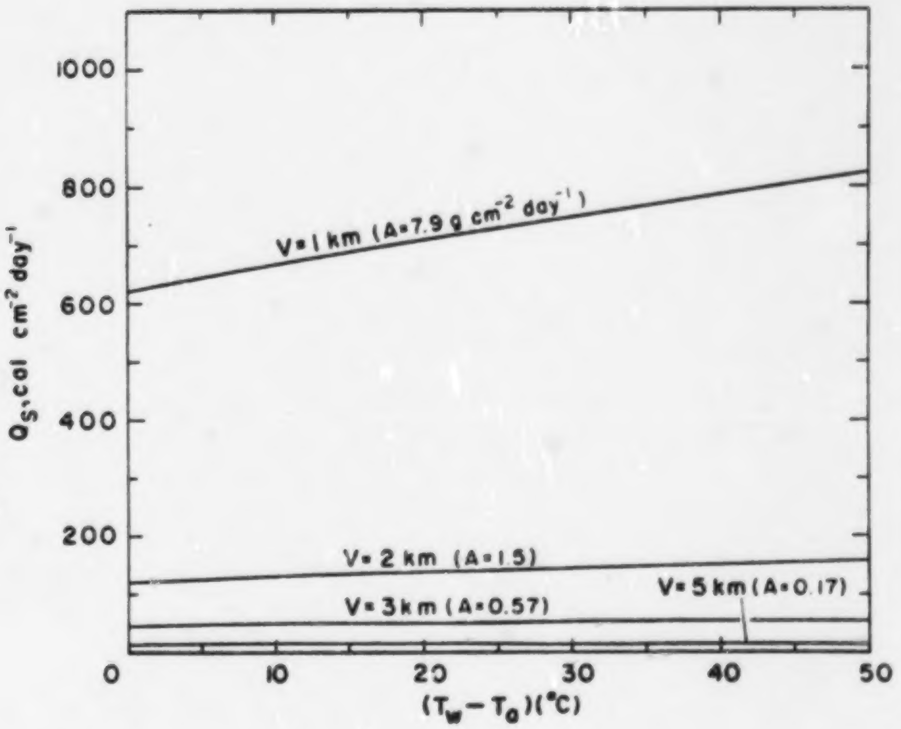

Fig. 4. Q_S vs $(T_w - T_a)$ at $v_a = 0$.

(Dinghan, Weeks, Yen, 1967)

"...The water temperature at the site of thermal pollution (x = 0) was calculated using eq 12. Simpson's rule was then used to compute the value of the integral and the corresponding value of x in 0.1K steps downstream until some cutoff temperature was reached. In the problems considered in this paper the cutoff temperature was 273.2K, the ice point.

"Figure 5 shows the form of a typical temperature vs distance curve....

"Experimental checks

"It is difficult to state the accuracy with which the approach outlined in this paper will permit the calculation of the position of the ice front. Besides the difficulty in accurately predicting Q^*, it is obvious that an ice sheet will not form exactly at the point where the water temperature reaches 0 C. Under conditions of intense turbulent mixing, frazil ice may form initially. Where vertical mixing is weak, the theoretical position of the ice sheet will in general also lie upstream from the actual ice front.

"It should be emphasized that this paper calculates only the steady-state ice-free reach. The calculations should, therefore, be most representative when the weather conditions and Q_p have been relatively constant. When either the air temperature or Q_p are decreasing with time the calculations should also be representative, because the position of the ice front should rapidly adjust to the new steady-state value. However, the length of the calculated ice-free reach may be in considerable error when an appreciable cold period is followed by a warming trend. During the cold period, ice will accumulate on the river below the position of the ice front. When the air temperature rises, some of this ice must melt as the length of the ice-free reach increases to the new steady-state value. The time required for this ice to melt will cause a time lag in achieving the new steady-state position of the ice front.

"Because of these difficulties and because many of the assumptions involved in writing eq 11 are not strictly true in a real situation, it is highly desirable to be able to compare field measurements of ice-free reaches below existing thermal pollution sites with computed values. Unfortunately, careful field observations of this phenomenon are extremely limited. However, it was possible to obtain unpublished data collected by the Corps of Engineers, St. Paul District, * regarding the length of ice-free reaches below the Northern State Power Company's Riverside and Highbridge steampower generating plants. These plants are located on the Mississippi River in the vicinity of Minneapolis-St. Paul and discharge thermal pollution directly into the river. As a test area this general reach of the Mississippi has several disadvantages: several other small plants discharge thermal pollution and small tow boats frequently pass up and down the river when ice conditions are not too severe. Both these factors undoubtedly disturb the natural development of an ice sheet. The extent to which they enlarge the ice-free reaches below the Riverside and Higbridge plants is unknown. Further, at a point 5 km below the Riverside plant there is a lock and dam complex,

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* M. Nelson, personal communication.

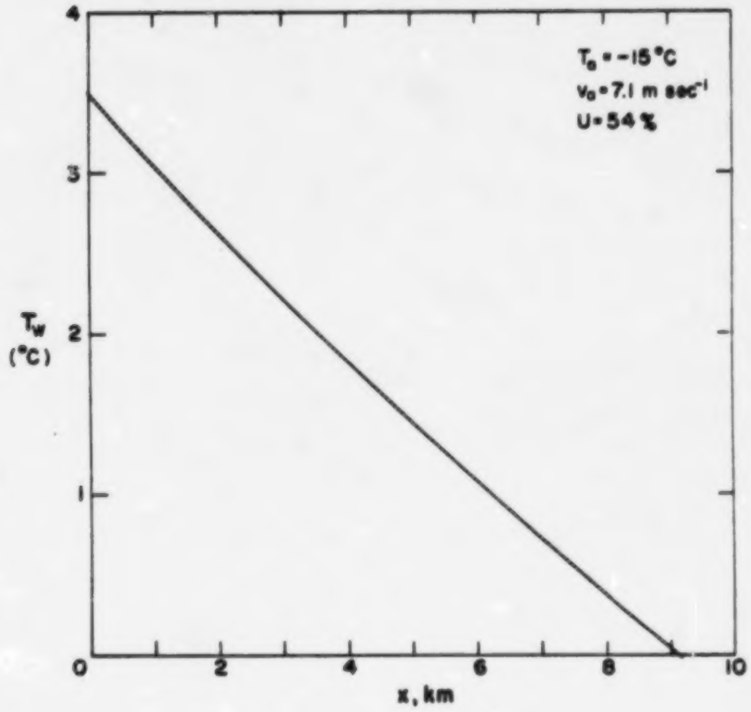

Fig. 5. Typical downstream temperature profile below a thermal pollution source.

(Dingham, Weeks, Yen , 1967)

and 6.4 km below the Highbridge plant a significant amount of thermal pollution is introducted by the Minneapolis-St. Paul Sanitary District plant. Therefore neither of these locations represents an ideal test site (i.e., a location where an isolated thermal pollution source introduces heat into a river that possesses relatively constant hydrometric parameters).

"The total area of open water below these two plants was determined from aerial photographs on several different dates during the winters of 1965 and 1966. Because the open water - ice boundary was usually quite irregular, the area of open water was converted to an effective length by dividing it by a representative width of the river...."

"The question immediately arises as to the time period over which the meteorological conditions should be averaged or, stated another way, how quickly the length of the open water reach responds to changes in meteorological conditions. While no study was undertaken to resolve this matter, Bilello's (1967) study of Seneca Lake, Michigan, suggests that near-surface water temperature trends follow air temperature trends with a lag of about 1 day. The work of Ince and Ashe (1964) on the St. Lawrence River suggests a similar response time. In most cases considered in the present paper, the length of time required for the water to traverse the ice-free reach is less than or only slightly greater than 1 day. Therefore, the average meteorological data from the date prior to the date of ice observation were used in calculating the length of the ice-free reach.

"Table I presents the observed ice-free areas below the thermal pollution sites and "observed" ice-free lengths calculated from these areas. Ice-free lengths calculated using the Kohler equation method and the Russian winter equation are also listed. In the calculations regarding the Highbridge plant, the calculated open reach is longer than the distance (6.4 km) to the next large thermal pollution source, the Minneapolis-St. Paul Sanitary District plant. Therefore, to calculate the total length of the open reach, the calculated water temperature 6.4 km below the Highbridge plant was taken as the natural water temperature T_{nat} when the thermal pollution associated with the Minneapolis-St. Paul Sanitary District plant is introduced. The final length of the open reach produced by both plants is then simply the length of the calculated reach below the Minneapolis-St. Paul Sanitary District plant plus 6.4 km.

"As would be expected from examining Figure 2, the lengths calculated by the Russian winter equation are always shorter than those calculated by using the Kohler equation method. They are also clearly in better agreement with the observed lengths. Figure 6 presents a plot of the observed lengths of the ice-free reaches against the lengths calculated using the Russian winter equation. The agreement is very encouraging.

Table I. Observed and calculated values for the areas and lengths of the ice-free reaches below thermal pollution sites along the Mississippi River, Minneapolis-St. Paul, Minnesota.

	Riverside				Highbridge			
			Calculated length				Calculated length	
Date	Observed area (km²)	"Observed" length (km)	Russian winter eq (km)	Kohler eq (km)	Observed area (km²)	"Observed" length (km)	Russian winter eq (km)	Kohler eq (km)
20 Jan 65	2.169	12.0	17.9	26.6	4.597	40.0	42.6	62.5
29 Jan 65	.777	4.3	4.3	7.0	.882	7.8	11.8	18.6
4 Feb 65	.890	4.9	5.8	10.0	1.036	9.0	15.1	25.6
11 Jan 66	---	---	---	---	2.428	21.2	15.7	21.8
14 Jan 66	2.023	11.3	16.0	28.9	4.233	36.8	41.3	73.2
24 Jan 66	1.311	7.3	3.2	5.8	1.546	13.4	12.1	21.2
28 Jan 66	1.287	7.2	3.5	5.3	1.076	9.4	10.4	13.8
23 Feb 66	2.161	12.0	17.1	60.8	5.063	44.0	39.5	124.6

(Dingham, Weeks, Yen , 1967)

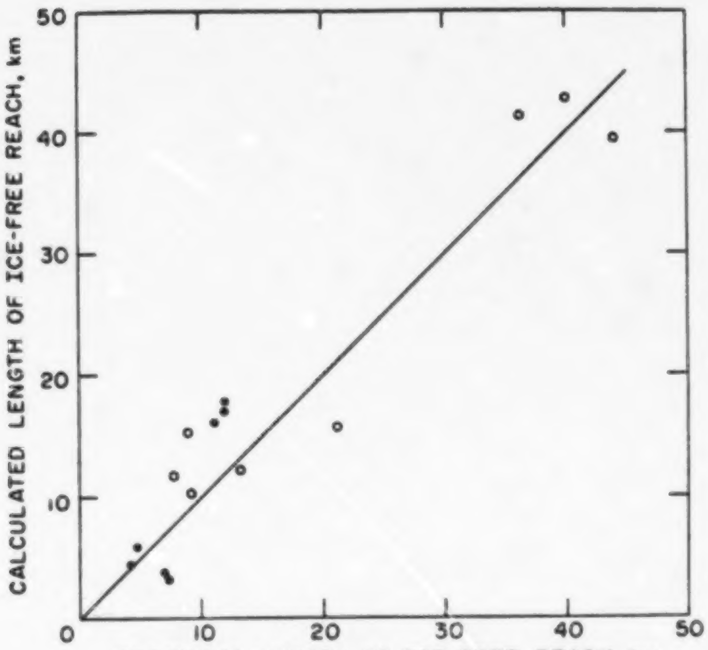

Figure 6. Observed vs calculated ice-free reaches. Measurements below the Highbridge Plant are shown as open circles and measurements below the Riverside Plant as dots.

313 (Dingham, Weeks, Yen , 1967)

Although there is a slight tendency for the calculated lengths to be longer than observed, no consistent pattern is apparent.

"Applications to the St. Lawrence Seaway

"The ship traffic on the St. Lawrence Seaway is completely stopped by ice for 3½ to 5 months each winter. Particular difficulty is encountered in the vicinity of the lock areas and ship canals. If these areas could be kept ice-free it would be possible to move shipping into the Great Lakes during most of the winter. This would be a great convenience and would save transportation costs of several million dollars per year. One conceivable way to accomplish this is to use the excess heat produced by nuclear power reactors to remove ice at critical locations. The production of electricity by nuclear power is now becoming commercially competitive with conventional forms of power production. In addition, the exact positioning of power reactors is not important as long as there is a major river nearby that can be used as a source of coolant and the reactor can be coupled with the general power grid system currently in use in eastern Canada and the United States. If it can be shown that the thermal pollution from a reactor is sufficient to keep a significant length of a shipping canal ice-free during the winter, a strong case can be made for positioning future reactors along the St. Lawrence River."

Recent studies by the Great Lakes Research Center, U. S. Lake Survey show that large lake areas critical to shipping (Mackinac Straights, Detroit River, Whitefish Bay, etc.) are closed a large portion of the winter season. In many cases observed, wind-driven ice causes the closure.

"Two types of nuclear reactors are considered here: those presently available with a thermal pollution output of 2.9×10^8 cal sec^{-1} ($\sim 1.2 \times 10^9$ watts) and those in the design stage with a thermal output of 8.4×10^8 cal sec^{-1} ($\sim 3.5 \times 10^9$ watts). As an estimate of extremely severe winter conditions for the general seaway area, a value of $T_a = -17C$ was used. This is based on the mean monthly minimum temperatures from Ottawa (January, -16.7C; February, -15.6C; 31 years of record) and Quebec (January, -16.1C; February, -15.6C; 32 years of record). A windspeed of 5 m sec^{-1} was assumed as representative, based on January and February data from Cornwall, Ontario. This windspeed is undoubtedly high because in the general St. Lawrence area low temperatures are usually associated with relatively calm conditions and pronounced radiational cooling. A representative average temperature for the seaway area during January and February is -11C.

"As an example the ship canal around the Montreal area is considered: the South Shore Canal with the St. Lambert and Cote St. Catherine Locks.

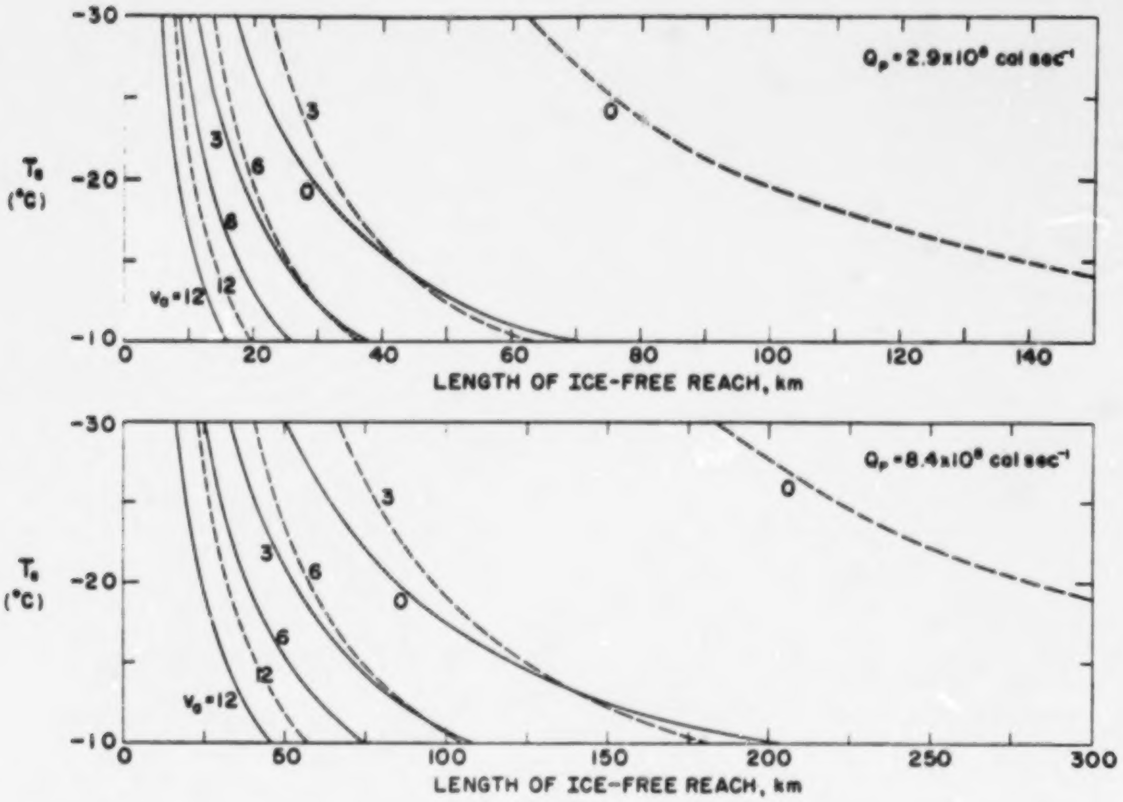

Figure 7. Length of ice-free reach as a function of air temperature (°C) and wind speed (m sec^{-1}): South Shore Canal, St. Lawrence Seaway. Solid curves are based on the Russian winter equation and the dashed curves on the Kohler equation method.

(Dinghan, Weeks, Yen, 1967)

In the fall and early winter the water temperatures in this area are 1 to 2 degrees lower than upstream in the vicinity of Cornwall; therefore, the South Shore Canal is the first location on the Seaway that encounters significant ice problems. The average width of the canal is 150 m, the depth is 9 m and the water flow velocity 0.5 m sec^{-1}. The length of the South Shore Canal from Montreal Harbor to Lake St. Louis is roughly 32 km. As can be seen from Figure 7 the lengths of the Canal that can be kept ice-free with T_a = -17C, v_a = 5 m sec^{-1} and C = 10 are 17 (Russian winter) and 25 km(Kohler's equation) using a conventional reactor. With a larger reactor the calculated lengths are 50 and 75 km respectively. If similar estimates are made by using the Russian winter equation and the average winter temperature of -11C, values of 27 and 75 km are obtained...."

Small (1955) feels that future power plants on the St. Lawrence from Lake Ontario to Montreal would greatly simplify keeping the river open between Lake St. Peter and Montreal Harbor. No computations to support this idea are given in the article.

Lambor (1957) discusses alteration of the thermal regime to overcome ice problems in river harbors.

> "Big thermo-power plants producing hundreds of megawatts draw approximately as much as 15 cu. m/sec, of water, which is released heated up to 10°C. Even a draft of 50 - 60 cu. m/sec for cooling purposes is no longer exceptional, and one must reckon with the steady increase of these quantities. The same volumes of cooling water are also required by power plants, operating on the nuclear energy principle. This consequently is a huge thermic reserve, which should not be neglected when it comes to the exploitation of the water track on whose banks the plant is located.
>
> "By suitable adjustment of the industrial plant requirements to those of the harbour of water track and with the corresponding reasonable designing of the industrial water circuit, it might be possible to considerably delay the freezing over of a river harbour, and even to entirely prevent the occurrence of ice phenomena there or else on the water track prolonging at the same time the exploitation period.
>
> "If we take a quantity of discharge water amounting to 15 cu. m/sec heated to 10°C, - this quantity not being anything exceptional in large industrial establishments - we obtain 1, 3×10^9 kal. supplied per day to the harbour basin. This is a quantity, which, in theory, would be capable of melting 15.400 (sic) cu. m of ice under an average temperature of -4°C and if supplied regularly, would allow for maintaining a minimum temperature of -4°C, and if supplied regularly, would allow for maintaining a minimum temperature of the harbour basin averaging +6°C, under which value ice phenomena will not occur, on condition of course that the water distribution in the basin is properly carried out. The permanent supply of this quantity of warm water would allow not only to maintain full activity in the harbour, but would also supply important thermic reserves for prolonging navigation conditions on the water route."
>
> "Closed circuits of clean cooling water should be replaced in winter by open circuits flowing through the harbour basin. Water discharge outlets located at low points in order to ensure a suitable degree of dilution, would have to be replaced during the winter season by surface outlets. At those places where tendencies of bottom ice formation appear, this moment would have to be carefully considered.

"Figure 4 shows an example of an electric plant located near a river harbour, where three kinds of water circulation are applied accounting for navigation requirements:

1. Partly closed circuit, with the cooling system based on tower coolers applied during low water level in the river, preventing excessive dilution in order to maintain suitable biological conditions.

2. Open circuit with water intake from the harbour basin with discharge into the river, applied in summer by water levels higher than the average. This will result in a partial circuit, but as it is shown on basis of thermic calculations, it can also be applied on large rivers which guarantee the maintaining of proper navigation depths on the route.

3. The open circuit applicable in winter would consist in taking water from the river and discharging it into the harbour basin."

"For all these problems, which undoubtedly form the basis of projecting work, not only standards and regulations of any kind are lacking, but also methods for carrying out complicated thermic calculations have not yet been worked out, so that results of calculations are often misleading and even contradictory...."

Golek (1957) noted a thermal regime alteration of the Vistula and Oder due to power plants.

"Relatively interesting is the late icing of the Vistula River in the vicinity of Warsaw, caused by the influence of Warsaw electrical power plants, yearly differing the icing conditions on its longer segment. This same phenomena also occurs on the central segment of the Oder River; in this instance, allowances being made due to the inflows having other causes, for instance, water management on the canal grades."

Siegfried (1957) describes thermal pollution which retards river ice formation.

"The formation of ice in canals and rivers may be retarded by warm water being added to the rivers due to ground water infiltration. Ground water may be pumped into canals or dam ponds or locks and will raise the temperature on the order of 11°C. Unfortunately, lowering of the water table may forbid the possibility of this intervention."

"Water used for industrial cooling may be pumped into rivers or canals leading to the halting of freezing of the upper layers of the river water. This is common on the lower Seine between the Gennevillier and Mericourt. The port of Dunkerque is also kept warmed by water from the refineries. This appears to be beneficial."

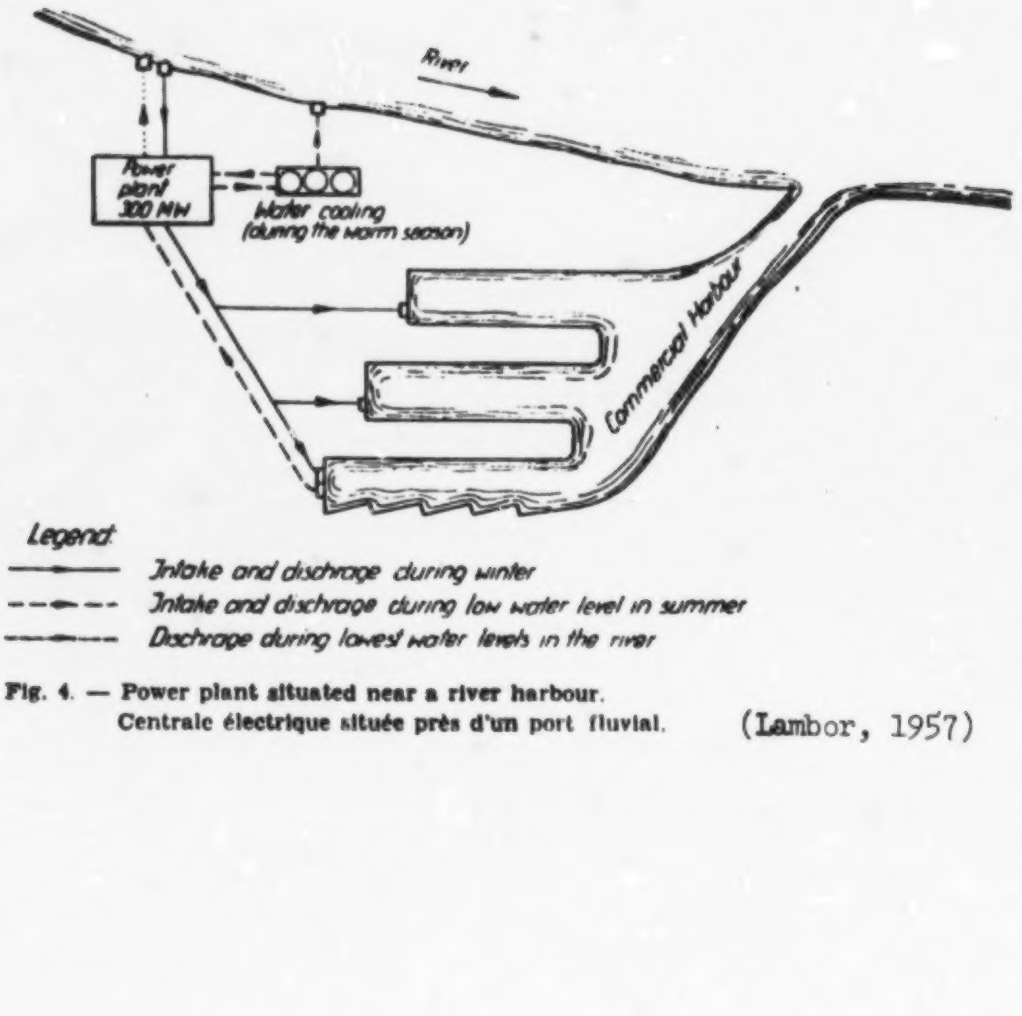
River
Power plant 300 MW
Water cooling (during the warm season)
Commercial Harbour
Legend
Intake and dischrage during winter
Intake and dischrage during low water level in summer
Dischrage during lowest water levels in the river

Fig. 4. — Power plant situated near a river harbour.
Centrale électrique située près d'un port fluvial. (Lambor, 1957)

"On the Seine downstream from Paris, ice is not a problem.... These exceptional circumstances are certainly due in part to a reheating of the water afforded by the central heating system of Paris. This is also due to the struggles against the ice covers upstream from Paris."

"Material may be added to the water to retard freezing. The addition of salt water to fresh water may lower the freezing point. Industrial acids and waste petroleum products have the effect of interrupting the freezing of the water."

The effects of steam electric and sewage plants on early river breakup in Alaska are mentioned by Cook and Wade in a report by the Rock Island District, Corps of Engineers (1967).

Brief mention of alteration river ice by a change in thermal regime is made by Kemmerikh (1958).

"Within the limits of the towns (cities) clearings form, sometimes, at points of discharge of industrial waste water."

Laktionoff (1957) comments on ice free areas in the tail waters of hydroelectric stations.

Rew (1958) describes a method of mixing warm water from a deep well with water from the Missouri River to combat ice troubles at the Council Bluffs, Iowa waterworks. The principle problem at the plant was formation of frazil and anchor ice at the bottom of settling and treatment basins.

"This blending of 54° well water with 33° river water gives a blended water temperature which is practically constant at 36°F. This provides a safe margin against freezing during the flow through the open basins. During prolonged sub-zero weather, it may be found necessary to increase the percentage of well water that is blended with river water. One winter's experience has proven this program to be an unqualified success."

Kienitz (1967) mentions alterations of the thermal regime of the Illinois Waterway (from Chicago to Grafton) by water from Lake Michigan and riverside industries.

Kerry (1946) speculates on the possibility of using the warmer waters of the Great Lakes to keep the St. Lawrence River ice-free. In conclusion he states: "There remains ... the two main problems of:

1) Designing outlets to the lakes so that only the 'warm' waters of the lakes will be drawn into the outflowing rivers.

2) To regiment the channels of the outflowing rivers so that the loss of heat from their surfaces will be reduced to a minimum."

Much discussion was prompted by Kerry's paper.

Peters (1946) states: "Evaporation is possibly one of the most weighty factors which bear on the balanced water levels throughout the Great Lakes Waterways. This point is brought forward merely to illustrate how delicate is the balance between supply and discharge, and how essential it is that none of the governing factors be disturbed without full knowledge of the ultimate effect....

"Some ten years past, certain studies were made of this balance between precipitation and evaporation, for the watersheds of the Great Lakes and the Ottawa River. For the forty-five year period 1890-1934, it was found that the average annual loss by evaporation was 66 per cent of the precipitation in the Great Lakes watershed, but only 45 per cent in the Ottawa watershed. This difference of some 20 per cent is probably due to the enormous areas of the Great Lakes.

"If this average of 66 per cent loss by evaporation were reduced to even 60 per cent, it would without doubt increase the discharge and therefore raise the average water levels throughout the waterways."

Altman and Moore (1946) object to Kerry's plan: "Freezing of flowing water is less affected by the loss of latent heat than by movement of the mass. Flow conditions, therefore, must be considered along with other factors when considering Mr. Kerry's recommendation for transference of 'hot' water from one location to another. The water may be kept free from icing by movement alone, but it will freeze over when velocity is low and depths are small."

A long intake channel is provided at a dam in California to control the thermal regime downriver (Engineering News-Record, 1967).

"... Engineers made the reinforced concrete intake big so it can draw off warm water from the tip, or cold water from the bottom of the reservoir.

"The intake runs 700 ft up the reservoir's 2:1 side slopes, spanning water temperature levels that vary as much as 25 deg between the bottom and top of the reservoir.

"With 26 temperature control shutters, 13 on each channel, the intake will be adjusted so water can flow from the reservoir at or about any pre-selected elevation. The shutters, 40 x 44-ft fixed wheel gates, will be inserted one at a time by a rail-mounted gantry at the top of the intake. They ride in a slot that parallels the intake's invert over its full length. When the shutters are stacked end to end in the slot, the water at the lower, colder depths can not enter the intake. Only the water above the last shutter installed can be drawn into the power plant and sent downstream. DWR says the intake provides one of the most flexible temperature controlling systems that has ever been used on a major hydro project."

Bird (1946) and Sexton (1946) also describe the use of warmer water from lower reservoir levels to prevent ice problems at a power dam.

Thermal regime modification

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Surface explosives

Surface explosives (C-4, Dynamite, ANFO, etc.) are used extensively in ice jam removal. Opinions on the effectiveness, types, and safety factors of surface explosives are varied. Van der Kley (1965) gives a brief introduction to the general properties of explosives.

"High explosives such as TNT, dynamite and guncotton are also combustible but they detonate or explode, which means that conversion into gas is practically instantaneous so that they have a shattering effect if confined. Detonation is brought about by the sudden application of a very high temperature or a very powerful blow that is capable of suddenly generating the necessary high temperature in the explosive."

"It is known that attempts were made 200 years ago (in Europe) to use explosives for clearing ice. It was not so much for the benefit of shipping as to remove the ice obstructing the river, which formed barriers and caused extensive flooding. Although scientists had discovered how to express the effect of explosives on solids as formulas by the end of the nineteenth century, they had not yet succeeded in producing a formula for their effect on ice. Tables showing the results of experiments conducted in the previous seventy years were the only source of information on the subject. People had to use their own judgment and the results of prior tests, if any were extant....

"As far as can be ascertained, the first attempts to clear ice by means of explosives were made in Germany in 1758. Bombs were affixed below the ice and exploded.

"Experiments were conducted more or less regularly after that, although the explosives used above or below the ice altered as time went by. They used bombs or gunpowder in wooden boxes or in bags made of cartridge paper dipped in pitch or in well caulked barrels."

"Steamboats were used to break the ice in the river Waal when it started to thaw in 1871, but gunpowder was also used to crack the ice with. Opinions on the general results were not unfavourable, but nothing definite was said about the part played by the explosions."

"Dynamite was used extensively in the winter of 1891. It became evident that this explosive produced fewer cracks than gunpowder. The main duty of the explosives squads was to clear the ice barriers that the steamboats could not reach.

"Explosives were also used in 1895 to assist the ice-breakers. Gunpowder was the explosive generally employed, but occasionally it was dynamite....

"Both explosives were used once more in the winter of 1917, chiefly to crack the ice in front of the ice-breakers so as to make their work easier. The ice-breakers do not appear to have benefited; ice in which holes had been blown with dynamite or gunpowder seems to have been just as difficult to deal with as ice that had not been touched. Observers said that explosives were of little use.

"The same method was adopted in 1929; once again explosives were used in advance of the ice-breakers. This time, however, TNT was employed and Thermit was tried a few times. The latter was not a success. Opinions now differed from those held in 1917; it was thought that cracking the ice with explosives ahead of the ice-breakers did make things somewhat easier for them.

"TNT was used again in 1940, both to condition the ice ahead of the ice-breakers and to break up the ice in places the ice-breakers could not reach. It is recorded that although the explosions made craters there were no cracks around them.

"Attempts were made in 1942 to remove an ice barrier ... with explosives. Sixteen charges of TNT weighing 10 Kgs each were exploded simultaneously. The holes to receive them were drilled deep enough and the charges were only 8 metres apart. In spite of that, the results fell far below expectations."

In discussing ice jam prevention and removal, however, Bezuglov (1959) feels that surface explosives provide the only effective tool for removal of jams which have already formed.

The following account indicates the trend in the use of surface explosives. It appears that explosives such as ANFO and C-4 are currently favored as tools for ice jam removal whereas in the past dynamite was extensively used. For convenience, manuscripts are reviewed here by explosive type. When the type of explosive is not stated in the original manuscript, the item is presented in the Dynamite Category.

ANFO

Hill (1964) describes the characteristics of ANFO.

"A blasting agent is a chemical or chemical compound that will detonate only with a powerful booster charge. This insensitivity is advantageous because such agents are not explosive until they are actually in holes and primed. Apart from the safety factor, there is considerable saving in cost through the elimination of special handling.

"The most widely used blasting agent is a combination of ammonium nitrate and fuel oil, usually abbreviated ANFO. The ammonium nitrate is in the coated prill form, used by farmers as fertilizer. The mixture is 6 percent by weight diesel fuel oil (one gallon per 100-pound sack of ammonium nitrate). This combination produces more gas per unit volume than any of the commonly known explosives. It releases about four times as much energy as ammonium nitrate alone; hence, theoretically, it would be three to four times as effective as the present standard ammonium nitrate cratering charge. Its low velocity of detonation, varying from 8,000 to 12,000 feet per second, and the large volume of gas produces the heaving effect desired in cratering or the breakage desired in quarrying....

"The principal disadvantage of ANFO is that it is adversely affected by water in amounts greater than 8 percent by weight. Although this can be partly overcome by placing it in polyethylene bags and doubling the primer, it is not entirely satisfactory, because the specific gravity of ANFO is slightly less than one and the material tends to float or rise to the top of the hole."

Wade (1966) reports on some ANFO tests. One objective of the investigation was: "To determine the optimum depth the explosives should be placed below an ice sheet to obtain maximum cracking rather than cratering effect from the charge."

In discussing the purpose and application of test results he states:

"Operation Peggy is a series of 6 - 80 lb. ANFO charges to be detonated under the ice in Peggy Lake (near Talkeetna, Alaska)....

"The data obtained from these experiments will be used to determine optimum depth for use in actual emergency operations on (ice jams in) the Yukon, Kuskokwim Rivers or in other areas. A further application will be to use the information obtained as reference for 'Operation Breakup' being conducted by the nuclear cratering group of Livermore, California, in February, on Blair Lake, near Fairbanks." See Kurtz, Bentler, Christopher, Frankenstein, Van Wyhe, and Rogusi (1966).

Charges and emplacements are also described: "The explosives for Operation Peggy will consist of 80 lbs. of ANFO in 16 gallon containers with two booster charges of C4 on the inside and exterior of the container."

His actual tests and snow and ice characteristics are summarized below.

"SHOT #1: (Fig. 3).
(1) Depth of Charge: 33 feet (bottom)
(2) Depth of Water: 33 feet"

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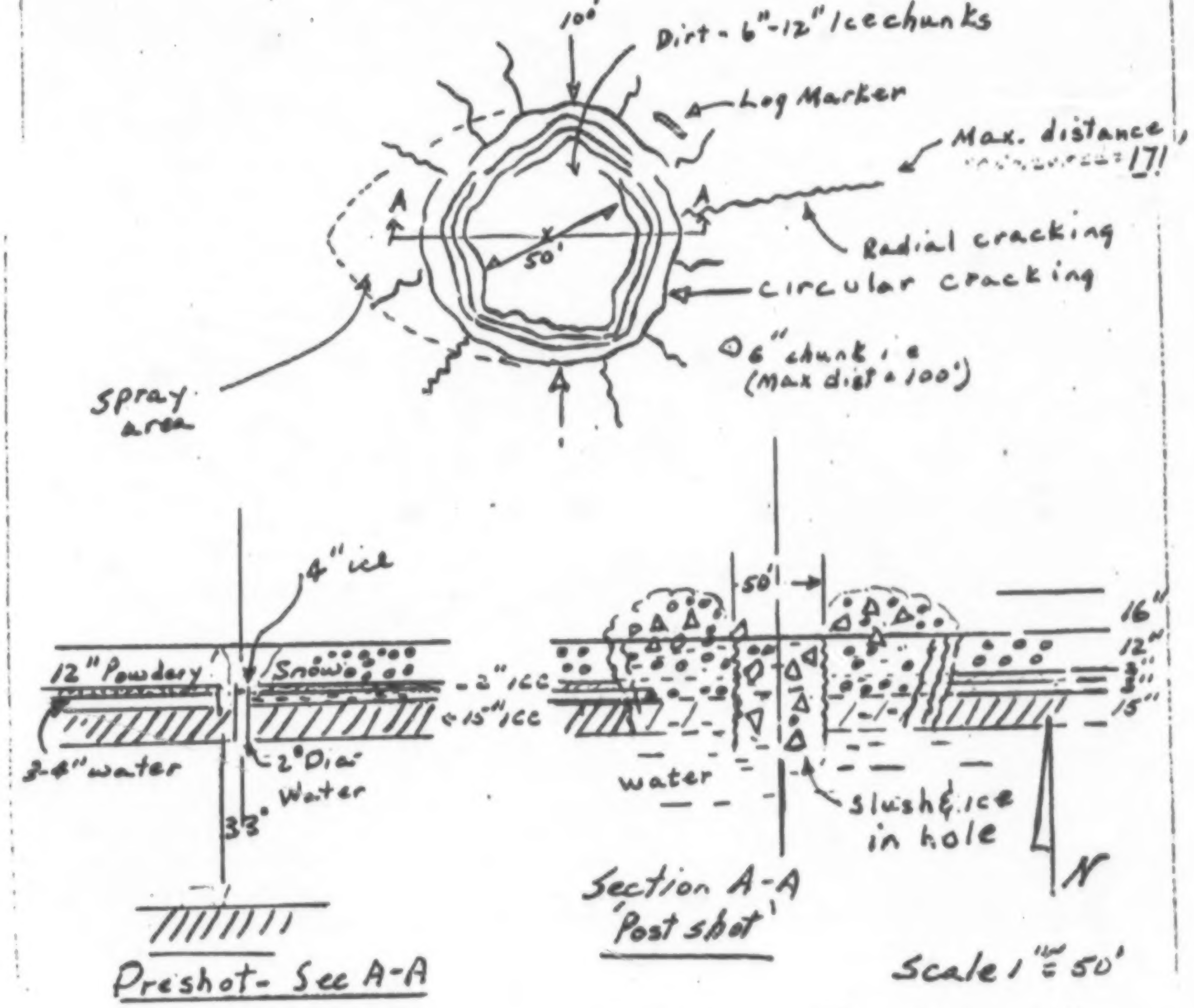
SUBJECT

Operation Peggy - Shot #1



100'
Dirt - 6"-12" Icechunks
Log Marker
Max. distance
measured = 171'
A
A
50'
Radial cracking
circular cracking
6" chunk ice
(max dist = 100')
spray
area
4" ice
12" Powdery Snow
2" ice
15" ice
3-4" water
2" Dia
Water
33'
50'
16"
12"
3"
3"
15"
water
slush & ice
in hole
N
Section A-A
'Post shot'
Preshot - Sec A-A
Scale 1" = 50'

FIGURE 3 329 (Wade, 1966)

Results of the shot were a 50 foot diameter crater "filled with slush ice, dirt and chunks of ice 6 to 18 inches in diameter."

"The area for a distance of 25 feet around the hole was filled with about 15 to 18 inches of slush ice, chunk ice and dirt. Several chunks of ice 6 inches in diameter ejected to a maximum distance of 100 feet.

"... Cracking occurred in several circular rings concentric to the crater and in relatively straight cracks radiating from the crater, as shown in Figure 3. The circular cracks started about 10 feet beyond the crater and the outside crack was 25 feet from the edge of the crater. Because of the snow and ice conditions, the observed cracking did not completely circle the crater; however, the 2 inch layer of ice was completely shattered and could not support weight for a distance of 25 feet around the hole. The radial cracks ran to a maximum length of 171 feet. In the paths where the snow had crusted, cracking was very evident. Several radial cracks 50 to 100 feet long were visible.

"... Four (4) inches of solid ice were observed on 5 February after 24 hours of sub-zero temperatures.

"SHOT # 2: (Fig. 4)
(1) Depth of Charge: 16 feet.
(2) Depth of Water: 22 feet."

Results of this shot were a 30 foot diameter crater "filled with snow, slush and ice chunks 12 to 24 inches in diameter. Very little dirt was thrown out of this hole. Some open water showed.

"... Slush ice and ice chunks 2 to 3 feet in diameter were thrown in about a 20 foot circle surrounding the crater.... The furthest distance that a 6 inch projectile flew was 70 feet. Circular cracking occured to a distance of 100 feet diameter with numerous cracks occurring adjacent to the hole. Extensive radial cracking occurred with cracks radiating to a maximum, observed length of 180 feet. Several radial cracks clearly showed branching, as shown in Figure 4....

"SHOT #3: (Fig. 5)
(1) Depth of Charge: 8 feet
(2) Depth of Water: 20 feet"

Results of this shot were a water gap 60 feet in diameter and the "crater was filled with slush ice, dirt and chunk ice 6 to 18 inches in diameter....

"The area surrounding the crater for about 10 feet was filled with 6 to 18 inch chunks of ice, dirt and slush ice.... The maximum distance that 6 inch chunks of ice were thrown was 50 feet.

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Operation Peggy - Shot #2

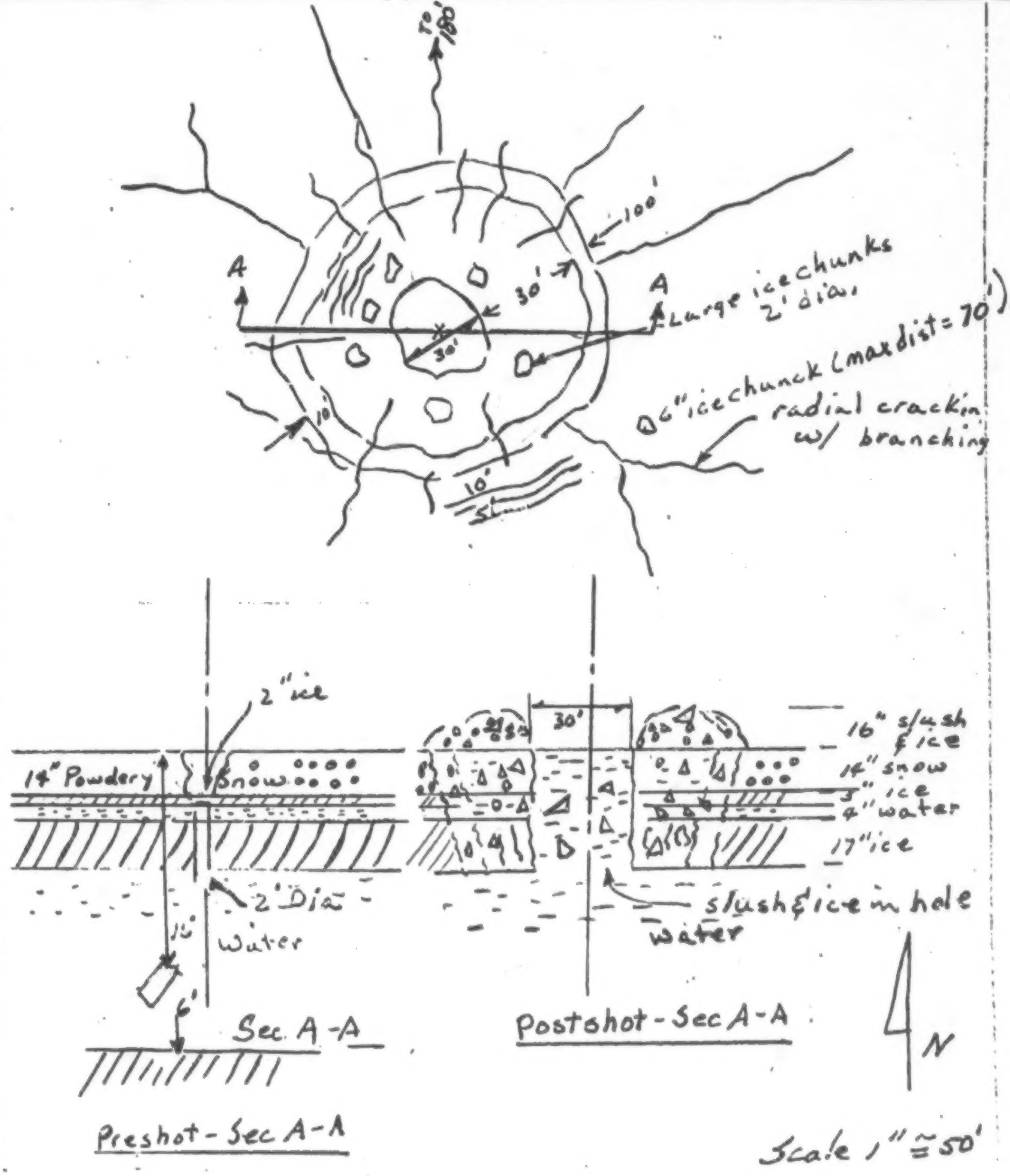
To 180'
100'
30'
A
A
30'
Large icechunks 2' dia.
6" icechunck (max dist = 70').
radial crackin w/ branching
10'
10'
5'
2" ice
14" Powdery Snow
2' Dia
10'
Water
6'
Sec A-A
Preshot - Sec A-A
30'
16" slush & ice
14" snow
3" ice
4" water
17" ice
slush & ice in hole
water
Postshot - Sec A-A
N
Scale 1" ≅ 50'

FIGURE 4 331 (Wade, 1966)

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SUBJECT ________

Operation Peggy - Shot #3

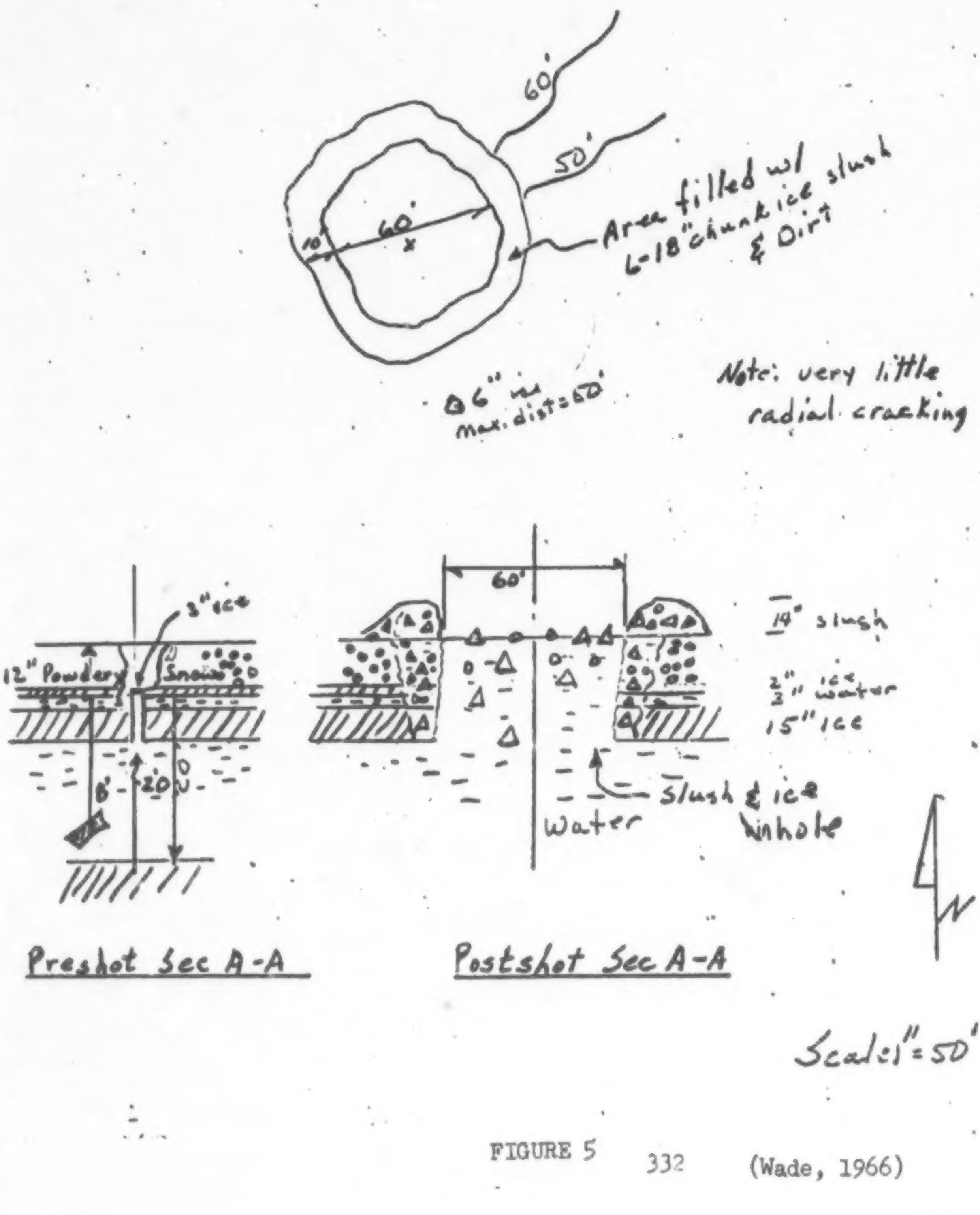
60'
50'
60'
10'
x
Area filled w/ 6-18" chunk ice slush & Dirt
Δ6" ice max. dist=50'
Note: very little radial cracking
3" ice
12" Powdery Snow
8'
20'
60'
14" slush
2" ice
3" water
15" ice
Slush & ice
Water
Whole
N
Preshot Sec A-A
Postshot Sec A-A
Scale: 1"=50'

FIGURE 5 332 (Wade, 1966)

"... Circular cracking occurred at about 40 feet from the center of the crater. Very little radial cracking was observed as shown in Figure 5...."

"SHOTS 4, 5 and 6: (Fig. 6)

"... Shots 4, 5 and 6 ... were detonated simultaneously and spaced 150 and 250 feet, as shown in Figure 6. These shots were set in 20 feet of water at a depth of 11 feet. They were allowed to freeze in over-night in sub-zero temperatures....

(1) Depth of Charge: 11 feet
(2) Depth of Water: 20 feet

"... All holes were 30 feet in diameter" and "... contained slush ice, ice chunks 6 to 18 inches in diameter and very little open water. Hole #6 contained dirt and sand intermixed. Holes 4 and 5 were slightly elongated ... while hole #6 was circular. The area immediately adjacent to the shots was covered with snow, slush ice and chunk ice piled to a depth of about 16 inches. Six (6) inch ice chunks were thrown to a maximum distance of 74 feet....

"Circular cracking was evident to a distance of 50 feet from the centers of the holes; however, the ice supported weight even though there was no noticeable intertie between shots 4, 5 and 6....

"Double Charge of ANFO: To test whether or not ANFO will deteriorate over a period of time, one hundred sixty ... pound charges were made up using year old fertilizer.... This fertilizer had been stored in open containers. The charge was detonated on top of the ice with the following results. Ice chunks 2 to 3 feet in diameter erupted from the hole and a crater about 30 feet in diameter was made."

Wade concludes: "The results of these tests confirmed that an 80 lb charge of ANFO is a satisfactory explosive that can be effectively used in emergency work. The optimum depth to place this charge is about 20 feet under the ice surface. Larger charges may require deeper depths; however, further work will be carried on in the river where deeper depths are obtainable....

"Data obtained on both circular and radial cracking is somewhat limited by the peculiar icing conditions that prevailed at Peggy Lake and to a lesser degree by the soft snow cover. Experience gained from previous testing indicated that more extensive cracking did occur."

Figure 7 shows the depth of charge as a function of the crater radius, maximum circular cracking radius and maximum radial cracking radius.

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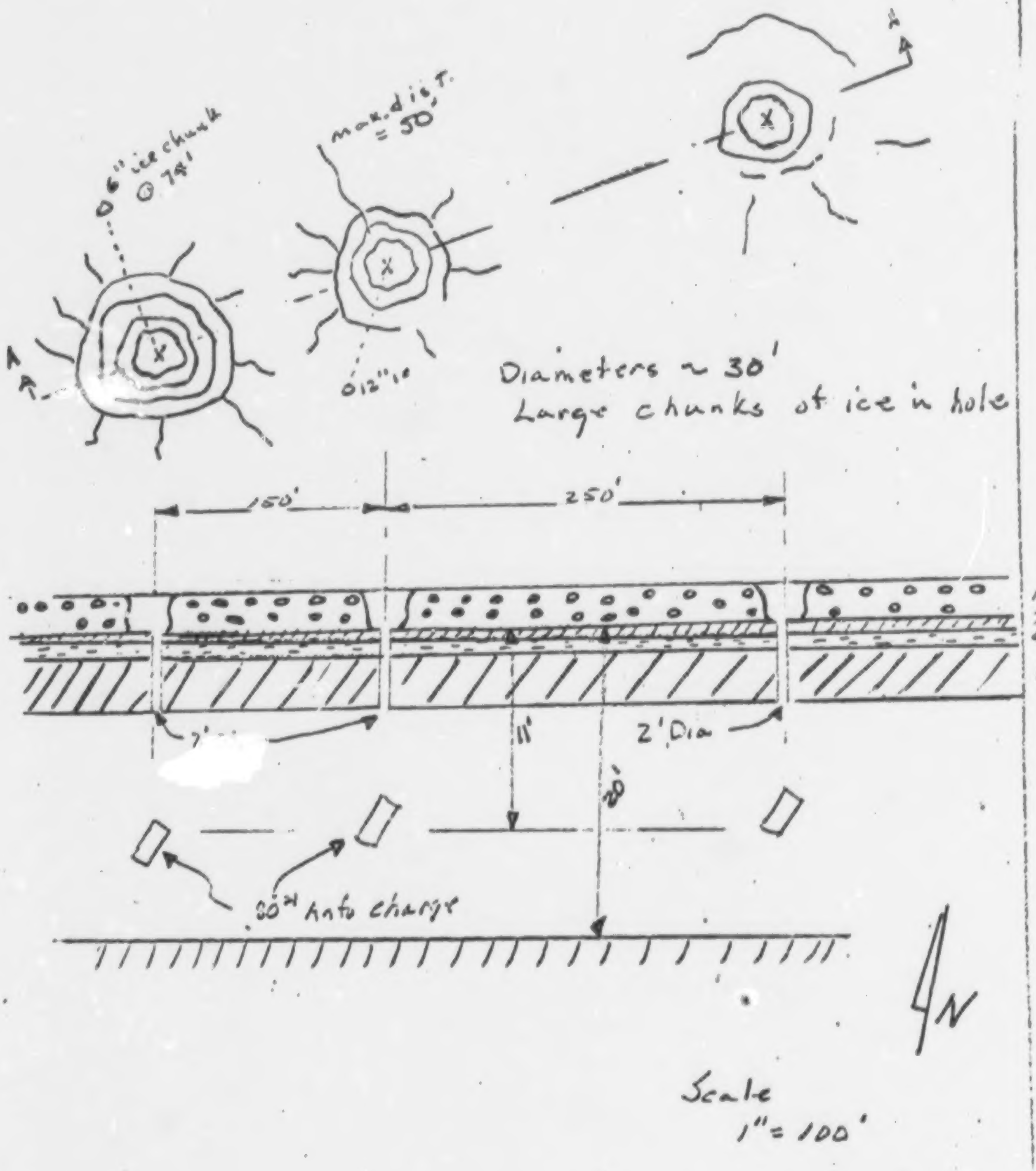
ANCHORAGE, ALASKA

SHEET NO.
FILE
DATE 7 Feb
COMP. [illegible]
CHKD.

SUBJECT: Operation Peggy - Shots 4, 5, 6



A
A
6" ice chunk @ 74'
max. dist. = 50'
12" @ 10'
A
A
150'
250'
15"
2"
6"
16"
2' Dia
11'
2' Dia
20'
20# Anfo charge
N

Diameters ~ 30'
Large chunks of ice in hole

Scale
1" = 100'

FIGURE 6 334 (Wade, 1966)

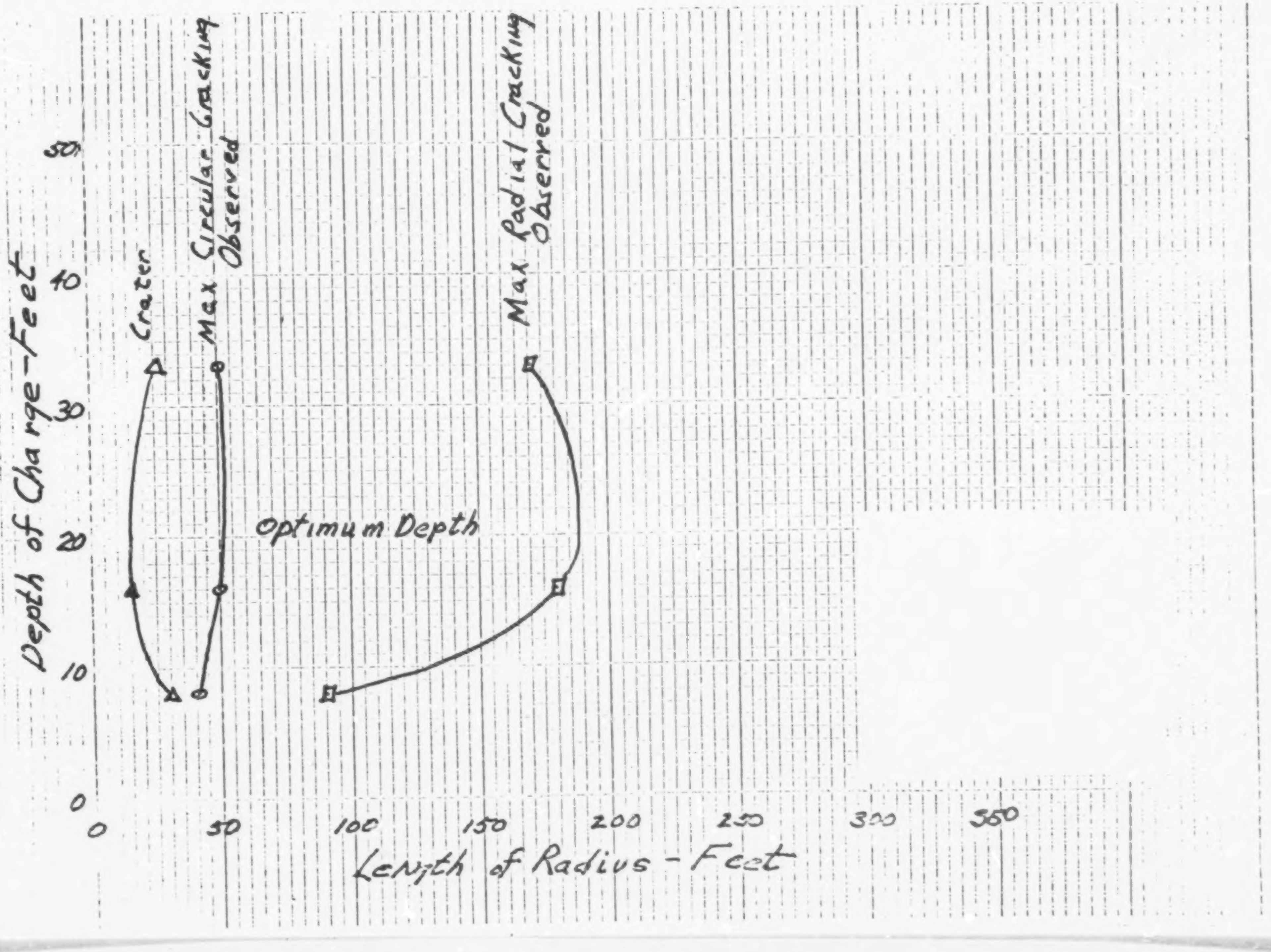


FIGURE 7

(Wade, 1966)

Froehle (1966) further describes the field tests reported on by Wade.

> "In the frozen lake, the purpose was to test the heaving effect that could be obtained. The lake ice was 16 to 18 inches thick. Placed 12 feet under the ice, a 40-pound charge of ANFO made a hole in the ice more than 50 feet in diameter and threw most of the ice clear of it. After the initial column of water rose into the air, a large quantity of mud and loose ice was forced out of the hole, and a wave effect could be felt 150 yards from the point of detonation. A 30-pound charge of ANFO gave similar results on a smaller scale. Each of the ANFO charges created a greater wave effect and larger ice-free area than did the standard cratering charge."
>
> "In the fight against nature in the Arctic, ANFO can become an extremely effective weapon. Its low cost (approximately 5 cents a pound), availability, and explosive qualities make it especially suitable for military field operations and disaster work in that region."

In a report by the Rock Island District, Corps of Engineers (1967) Wade describes another ANFO operation in Alaska.

> "Copper Center Operation of 1964-1965:
>
> (1) On about 10 December 1964, the Klutina River at Copper Center, Alaska, froze completely to the bottom, resulting in glaciation and overbank flow....
>
> (2) As a result of emergency conditions and the materials available, various new methods of ice jam alleviation were attempted....
>
> (3) After eight days of continuous effort, a channel 4500 feet long was established from the junction of the Copper and Klutina Rivers upstream to the Valdez highway bridge. The channel was established by first using a shaped charge to blast a hole into the ice, then placing a 40-pound cratering charge and blasting a crater. The craters were overlapped so that the river would have a new channel in which to flow.... All obstructions to the river flow were removed and the river was back in its normal channel. About 13,380 pounds of shaped and cratering charges (Table 2) were used.... Jamming along the Copper River downstream of the Klutina River was weakened and relieved by bombing...."

A detailed procedure for preparing and placing ANFO charges is given in the report by the Rock Island District, Corps of Engineers (1967).

TABLE 2

COPPER CENTER

Hand-Placed Demolitions - December 1964

Date of Operation	Shaped Charges lb.	Cratering Charges lb	C-4 lb.	Dynamite lb.	Total lb.
Dec 18	600	600	-	-	1200
" 19	1200	1300	-	-	2500
" 20	500	200	25	75	800
" 21	500	800	25	75	1400
" 22	1840	1840	-	-	3680
" 23	1850	1850	100	-	3800
	6590	6690	150	150	13,380

NOTE: The above demolitions were used to open a channel from the highway bridge to the confluence of Klutina River with the Copper River. (Rock Island District, 1967)

C-4

Composition C-4 is principally used as a main or booster charge for cutting and breaching. The smallest cap required for detonation is a special blasting cap of electrical or non-electrical type. The relative effectiveness as an external charge is 1.34 (TNT=1.00) and the velocity of detonation is 26,000 fps. The intensity of poisonous fumes is slight and its water resistance is excellent (Department of the Army, 1962). C-4 is also used as a booster charge for ANFO (Froehle, 1966).

One of the most recent papers on the use of C-4 in breaking ice is by Kurtz, Benter, Christopher, Frankenstein, Van Wyhe, and Rogusi (1966). An objective of their tests was to determine possible civil applications of ice cratering with explosives to prevent or clear ice jams and maintain ice free waterways. They concluded: "the explosive charge and firing procedures used are adaptable for civil applications - such as demolition of ice jams during domestic emergency operations."

"Operation BREAKUP, FY 66, was a series of small single and row charge chemical explosive detonations fired in fresh water to crater the overlying sheet ice."

"The technical objectives of the experiments were:

1. To determine the relationship between depth of detonation and the size of the water gap produced in ice-covered water bodies by underwater explosions.

2. To determine the effect of boundary reflection of the explosive shock wave on the relationship indicated above.

3. To determine the effect of charge spacing on the size and shape of the water gap resulting from the detonation of a row of charges.

4. To determine the effect of charge yield and emplacement depth on crack propagation.

5. To support theoretical studies of row cratering by observing surface motion phenomena, crack propagation, and bubble coalescence."

The location of tests was Blair Lake, 33 miles SSE of Fairbanks, Alaska.

"This lake is approximately one mile in diameter, with depths of 40 to 52 feet over an area 2500 x 2300 feet. In the Blair Lake area the extreme temperatures for mid-February are -55° to +48° F, with averages of -25° to +15° F; the ice is normally 30 to 40 inches thick with 22 inches average snow cover."

"Experimental plan

"Basic Charge Design ... They consisted of 136 pounds of composition C-4 encased in an aluminum sphere and center detonated by two SE-1 high energy exploding bridge wire detonators with two ½" x ½" tetryl pellets as booster." (Fig. 2.1)

"Figure 2.2 shows the 940-pound charge design used for the yield scaling experiments. Previous experiments had shown that charges of approximately 40 pounds would successfully crater two feet of ice. With three feet expected at Blair Lake, it was decided to increase the charge weight accordingly....

"Charge Emplacement Scheme. Figure 2.3 shows the typical charge emplacement.... Refreezing was provided for in the schedule rather than to attempt to displace the charge under the ice so that it would not be below the emplacement hole.

"The charges were emplaced by lowering the sphere through a hole in the ice to the desired depth and securing the lowering line to a rigid support bridging the ice hole....

"Minimum Spacing. Figure 2.4 shows the minimum charge spacing specified for layout of the detonations. The 300-foot separation was selected to minimize the effects of adjacent detonations on charges already emplaced and on the area of the expected crater.

"Consideration of Bubble Phenomenon. Explosions in water generate gas bubbles that have been well defined for TNT. The gas bubble pulsates rapidly under the hydrostatic pressure of the water and also migrates to the surface because of buoyancy. It was believed that the proximity of the bubble to the ice surface and the bottom would be important in the crater mechanism because 'blowout' or venting of the gases imparts additional velocity to the ejecta. In addition, the size and location of the gas cavity affect the path of shock waves reflected from either the ice layer or the bottom.

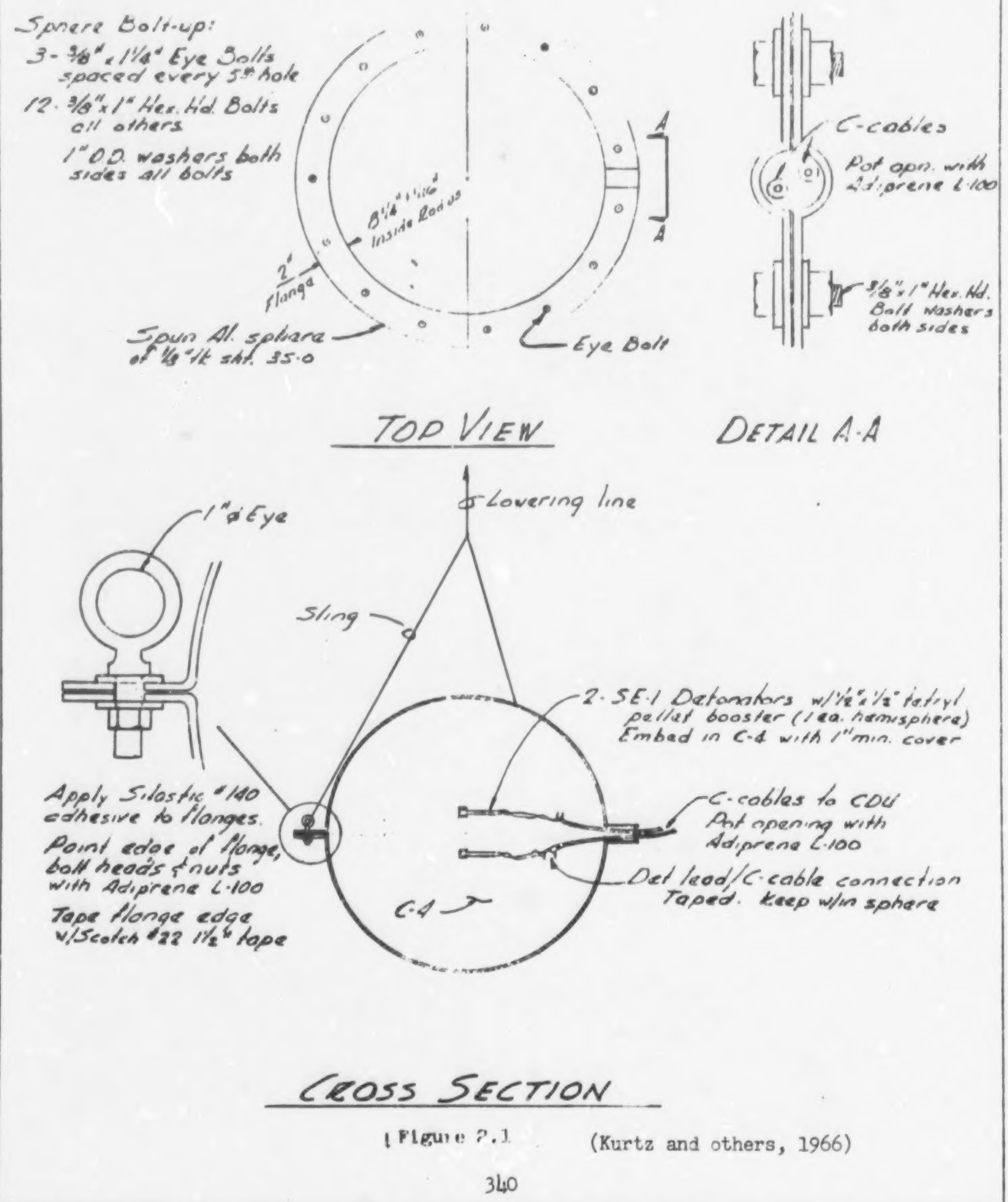
"The comparative bubble effectiveness of C4 was assumed to be equal to TNT. The following equation, derived by Cole (1948) for underwater explosions, was used to estimate the bubble size for 136-pound C4 explosions in water under ice:

$$R_b = 12.8\left(\frac{W}{Z + 34}\right)^{1/3}$$

SUBJECT 136 lb SPHERICAL CHARGE OPERATION BREAKUP

NAME Reimboldt

DATE 1 17 66


Sphere Bolt-up:
3 - 3/8" x 1 1/4" Eye Bolts spaced every 5th hole
12 - 3/8" x 1" Hex. Hd. Bolts all others
1" O.D. washers both sides all bolts
8 1/4" ± 1/16" Inside Radius
2" Flange
Spun Al. sphere of 1/8" 1k sht. 35-0
Eye Bolt
A
A
TOP VIEW
C-cables
Pot opn. with Adiprene L-100
3/8" x 1" Hex. Hd. Bolt washers both sides
DETAIL A-A
Lowering line
1" ø Eye
Sling
2 - SE-1 Detonators w/1/2" x 1/2" tetryl pellet booster (1 ea. hemisphere) Embed in C-4 with 1" min. cover
Apply Silastic #140 adhesive to flanges.
Paint edge of flange, bolt heads & nuts with Adiprene L-100
Tape flange edge w/Scotch #22 1 1/2" tape
C-cables to CDU Pot opening with Adiprene L-100
Det lead/C-cable connection Taped. keep w/in sphere
C-4
CROSS SECTION

[Figure 2.] (Kurtz and others, 1966)

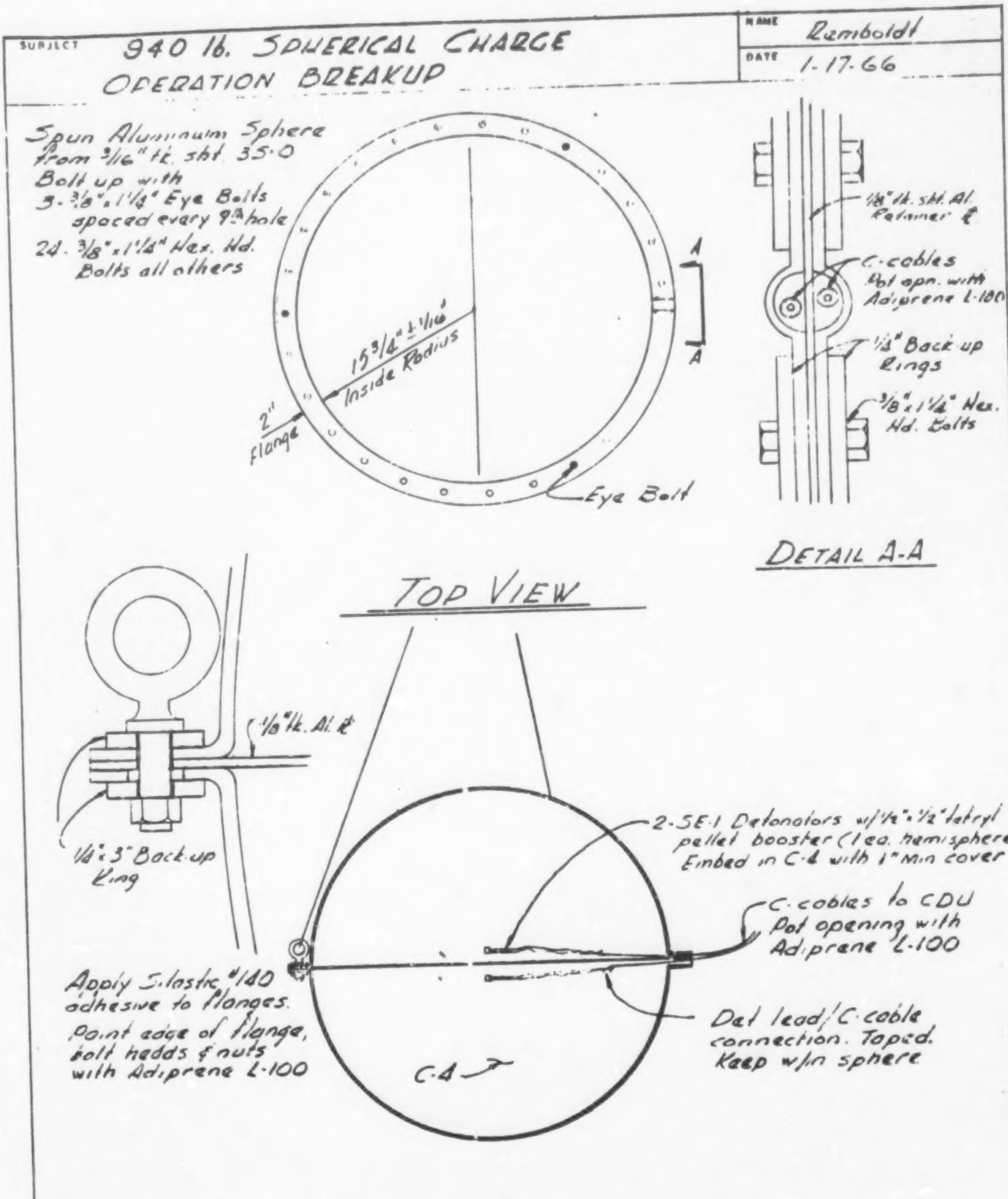

SUBJECT
940 lb. SPHERICAL CHARGE
OPERATION BREAKUP
NAME Remboldt
DATE 1-17-66
Spun Aluminum Sphere from 3/16" tk. sht. 35-0
Bolt up with
3-3/8"x1 1/4" Eye Bolts spaced every 9th hole
24-3/8"x1 1/4" Hex. Hd. Bolts all others
15 3/4" ± 1/16" Inside Radius
2" Flange
Eye Bolt
A
A
1/8" tk. sht. Al. Retainer R
C-cables Pot opn. with Adiprene L-100
1/4" Back-up Rings
3/8"x1 1/4" Hex. Hd. Bolts
DETAIL A-A
TOP VIEW
1/8" tk. Al. R
1/4"x3" Back-up Ring
2-SE-1 Detonators w/1/2"x1/2" tetryl pellet booster (1 ea. hemisphere) Embed in C-4 with 1" Min cover
C-cables to CDU Pot opening with Adiprene L-100
Apply Silastic #140 adhesive to flanges.
Paint edge of flange, bolt heads & nuts with Adiprene L-100
Det lead/C-cable connection. Taped. Keep w/in sphere
C-4
CROSS SECTION

Figure 2.2 (Kurtz and others, 1966)

SUBJECT CHARGE EMPLACEMENT SCHEME

NAME KURTZ

DATE 31 Dec 65

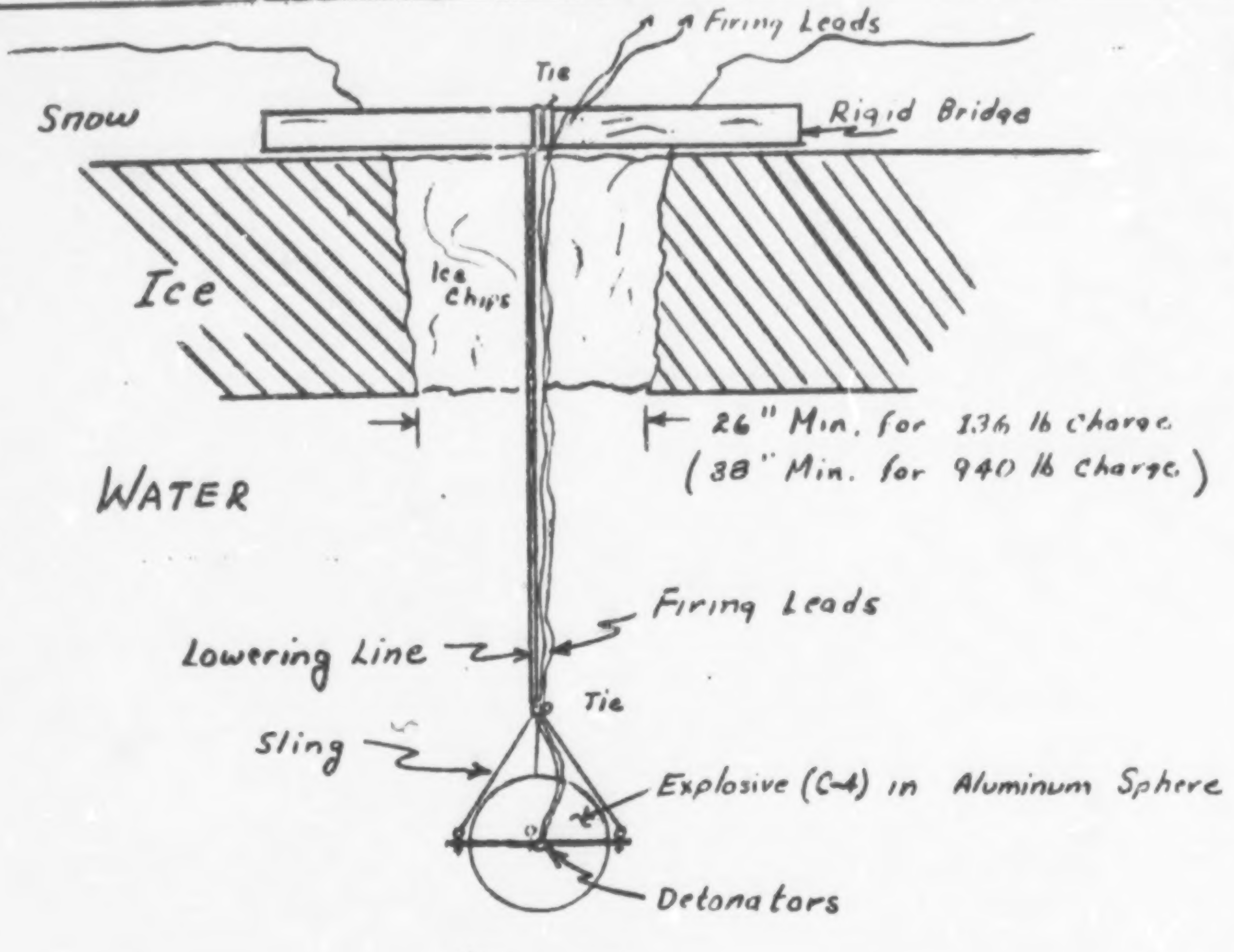

Firing Leads
Tie
Snow
Rigid Bridge
Ice
Ice Chips
26" Min. for 136 lb charge
(38" Min. for 940 lb charge)
WATER
Firing Leads
Lowering Line
Tie
Sling
Explosive (C-4) in Aluminum Sphere
Detonators

Figure 2.3

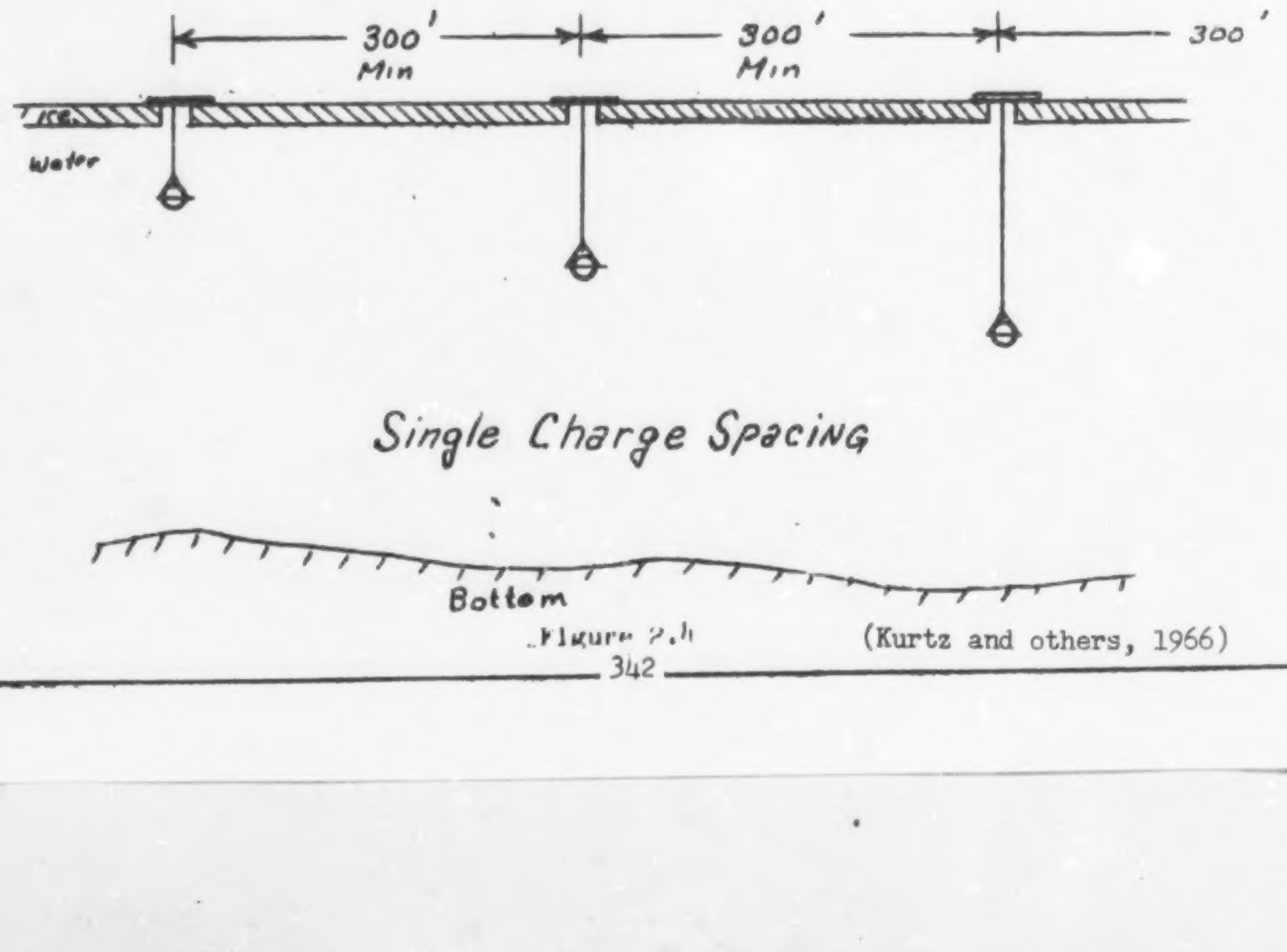

300' Min
300' Min
300'
Ice
Water
Single Charge Spacing
Bottom

Figure 2.4 (Kurtz and others, 1966)

R_b = buble radius in feet in fresh water
W = yield in pounds
Z = depth of burst below top of ice

"It was assumed that this relationship could be used to estimate bubble volumes for all depths of burst below a 3-foot ice layer on water 10 to 52 feet deep. The effective radius of the distorted bubble for the shallower shots was then derived from this volume estimation.

"The depth of burst also has a profound effect on the size and velocity of the bubble as it reaches a superimposed ice layer in its upward migration. Under certain conditions (observed in previous experiments of the Naval Ordnance Laboratory) the bubble growth assists materially in formation of the crater. The 'optimum' depth of burst for ice two feet thick is approximately $2W^{1/3}$ feet. At a depth of burst approximately equal to the bubble radius, or $4W^{1/3}$ feet, the bubble collapsed just prior to venting with a resultant increase in crater radii. Figure 2.5 presents an inferred qualitative description of this phenomenon which has been scaled from 300-pound TNT charge phenomena reported by Cole (1948) for free water....

"Single Charge Deep Water Calibration Series. Figure 2.6a shows the charges detonated to determine the relationship between depth of detonation and water gap produced in the ice as measured by R_a, the apparent radius of the crater. It was believed that the optimum radius would be between the bottom of the ice and $2W^{1/3}$ feet (approximately 10 feet). In addition to scheduling shots to define this region, deeper shots were planned to define the effects from bursts deeper than optimum.

"Row Charge Detonations. The five charges for the Row A were set at the optimum depth as determined by the single charge calibration series and were spaced one 'optimum' hole radius apart. The charges for Row B were set at the same depth but were spaced $1\frac{1}{2}$-hole radii apart. (Figures 2.7a and 2.7b). These rows were designed to observe any possible effects of bubble coalescence.

"Bottom Reflection Series. Figure 2.6b shows the various depths of burst and bottom depths selected for study of the effect of the proximity of the bottom for shallow water shots. It was believed that under proper conditions the shock wave reflected from the bottom could enhance the crater dimensions. The results of these tests, as evidenced in the crater radius, were used as the basis for design of emplacement depth for the yield scaling shot and for another row detonation.

"Upon completion of the series, it appeared that there was no additional enhancement of crater radius over that determined as optimum in the deep water calibration series. In fact, for all shots detonated, the radii were significantly less and there were no reflection phenomena or mechanism visible to the eye.

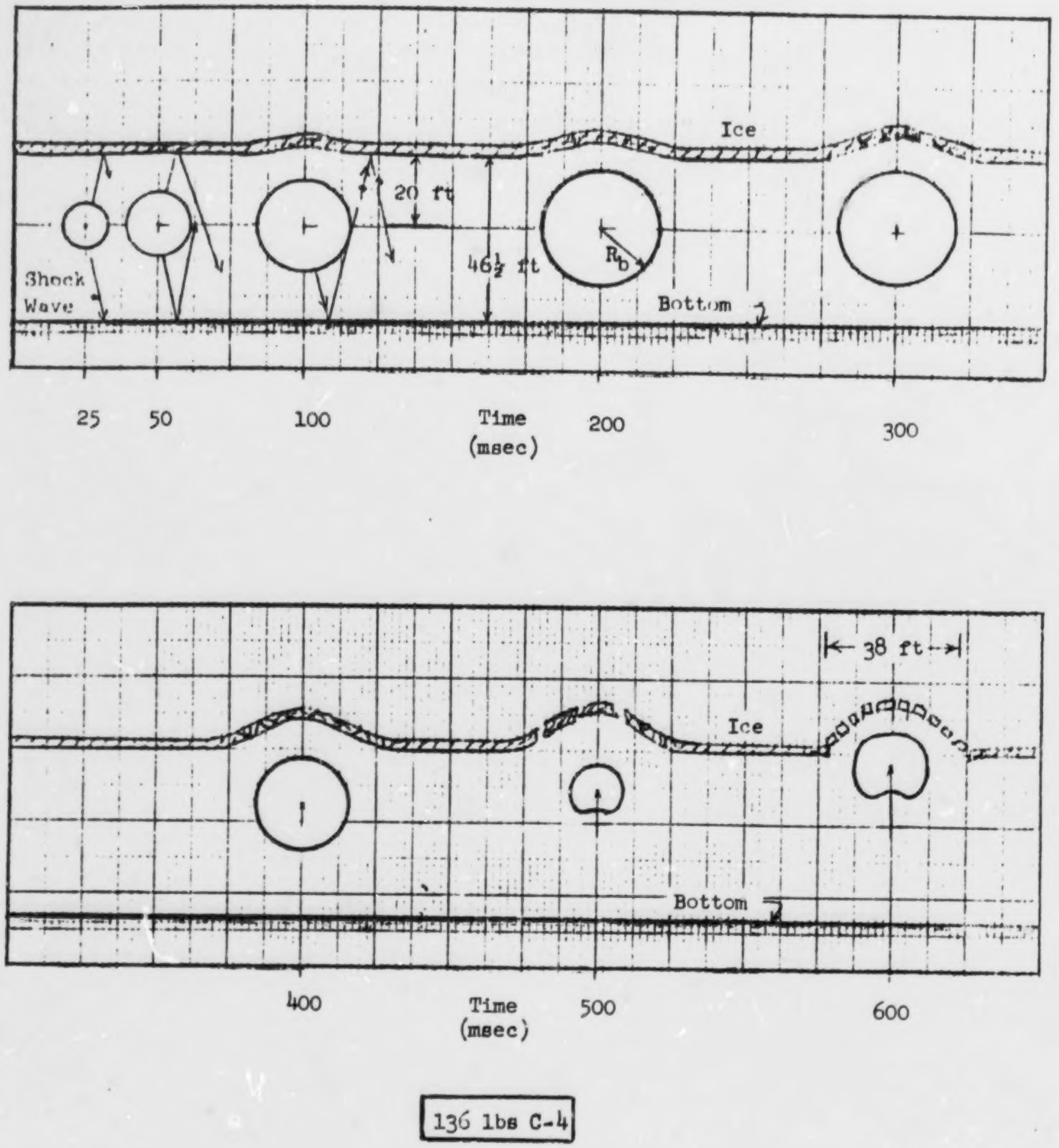
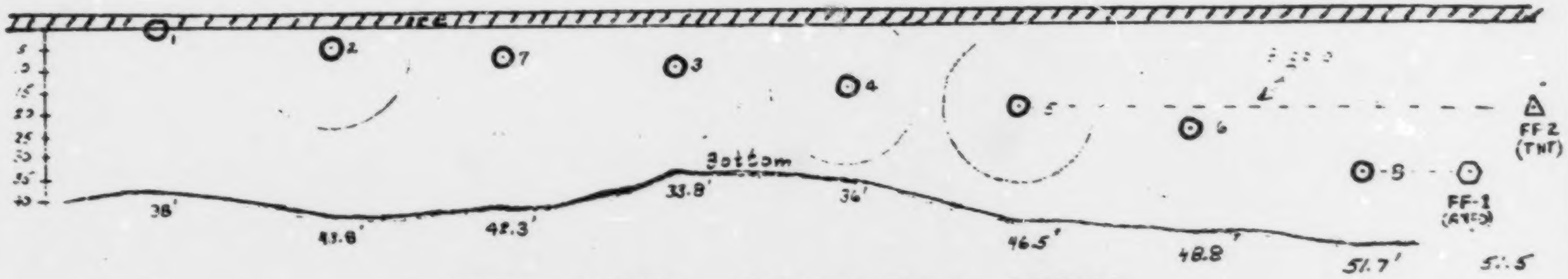
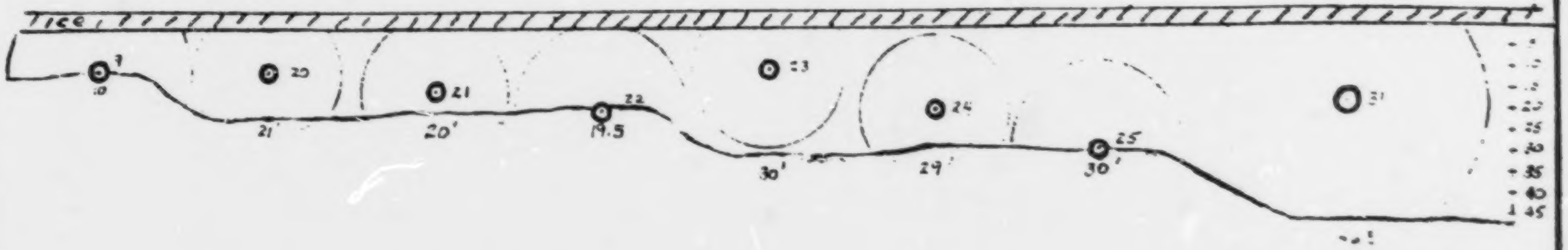

Ice
20 ft
46½ ft
Shock Wave
R_b
Bottom
25
50
100
Time (msec)
200
300
38 ft
Ice
Bottom
400
Time (msec)
500
600
136 lbs C-4

Figure 2.5 Qualitative Description of Bubble Development, Pulsation, and Migration for Conditions Analogous to Shot 5. (Inferred from scaling Cole's 300 pound TNT free water bubble phenomena$^{(12)}$ and from NOL observations of ice cratering$^{(4,5)}$.) (Kurtz and others, 1966)


ICE
1
2
7
3
4
5
6
8
FF 2
(TNT)
FF-1
Bottom
5
10
15
20
25
30
35
40
38'
43.8'
42.3'
33.8'
36'
46.5'
48.8
51.7'

DEEP WATER CALIBRATION SERIES

Figure 2.6a


ICE
9
10
20
21
22
23
24
25
31
21'
20'
19.5
30'
29'
30'
5
10
15
20
25
30
35
40
45

BOTTOM REFLECTION SERIES

Figure 2.6b

SCALING SHOT

Figure 2.6c

SINGLE CHARGE EMPLACEMENT

Figure 2.6 (Kurtz and others, 1966)

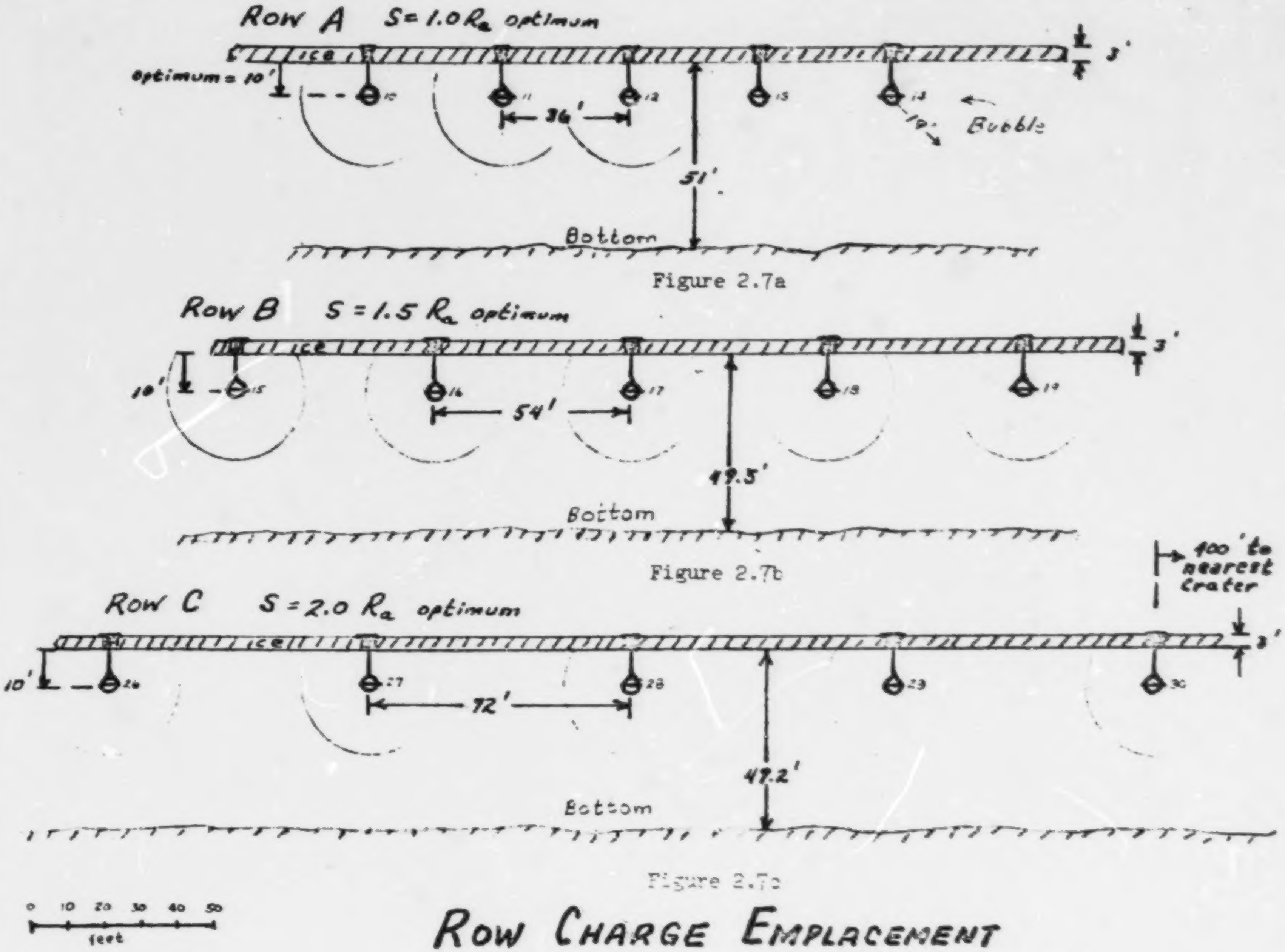

Row A S=1.0 R_a optimum
ice
optimum = 10'
3'
10
11
12
13
14
36'
51'
19'
Bubble
Bottom
Row B S = 1.5 R_a optimum
ice
10'
3'
15
16
17
18
19
54'
49.5'
Bottom
Row C S = 2.0 R_a optimum
ice
10'
3'
100' to nearest crater
26
27
28
29
30
72'
47.2'
Bottom
0 10 20 30 40 50
feet

Figure 2.7a

Figure 2.7b

Figure 2.7c

ROW CHARGE EMPLACEMENT

Figure 2.7 (Kurtz and others, 1966)

"Optimum Row Detonation. Utilizing experience from the earlier tests, Row C was designed in the field with charge spacings designed to produce a maximum water-gap.

"Earlier tests indicated that no advantage was to be gained from selecting shallower water. The depth of burst was selected as that which produced the greatest single charge radius (10 feet or optimum).

"Results of Rows A and B indicated that even greater charge separation might produce a larger crater width and thereby better define a more useful separation for use in practical application of the experimental results. Accordingly, a large step was taken to increase the charge spacing to 2.0 single charge 'optimum' hole radius apart. It was believed that the attendant cracking would be adequate to join all holes and produce a single water gap. (Figure 2.7c).

"Yield Scaling Shot. To obtain scaling information, a shot several times larger than the 136-pound shots was scheduled for the same 'scaled' depth of burst. The 940-pound charge was fabricated for this purpose. Earlier smaller scale experiments by NOL and others indicated that the cube-root scaling approximation could be used. Although the thickness of the ice was left unchanged (and hence was relatively thinner), the depth of burst was selected as 19 feet or 'optimum' based on $W^{1/3}$ scaling of the results of the cratering calibration series. The bottom was located in the deeper part of the lake to minimize the unpredictable effects. Figure 2.6c shows the relative charge geometry in comparison to all prior single charge detonations."

"Crater measurements

"Experimental procedures

"Definitions.

(1) Crater radius, R_a. R_a is the radius of the crater in which the ice has been severely disturbed.... (W_a is used for row widths.)

(2) Outer boundary of continuous ejecta radius, R_{eb}. R_{eb} is the radius of material that completely covers the preshot surface....

(3) Extreme range of missiles, R_{me}. R_{me} is the range to the outermost missile. The minimum missile weight considered was one pound.

"Determination of Crater Size. Four diameters of single-charge craters and nine widths and the length of row craters were recorded, as shown in Figure 4.1 ... The average row-charge crater width was determined from measurements 3 through 9.

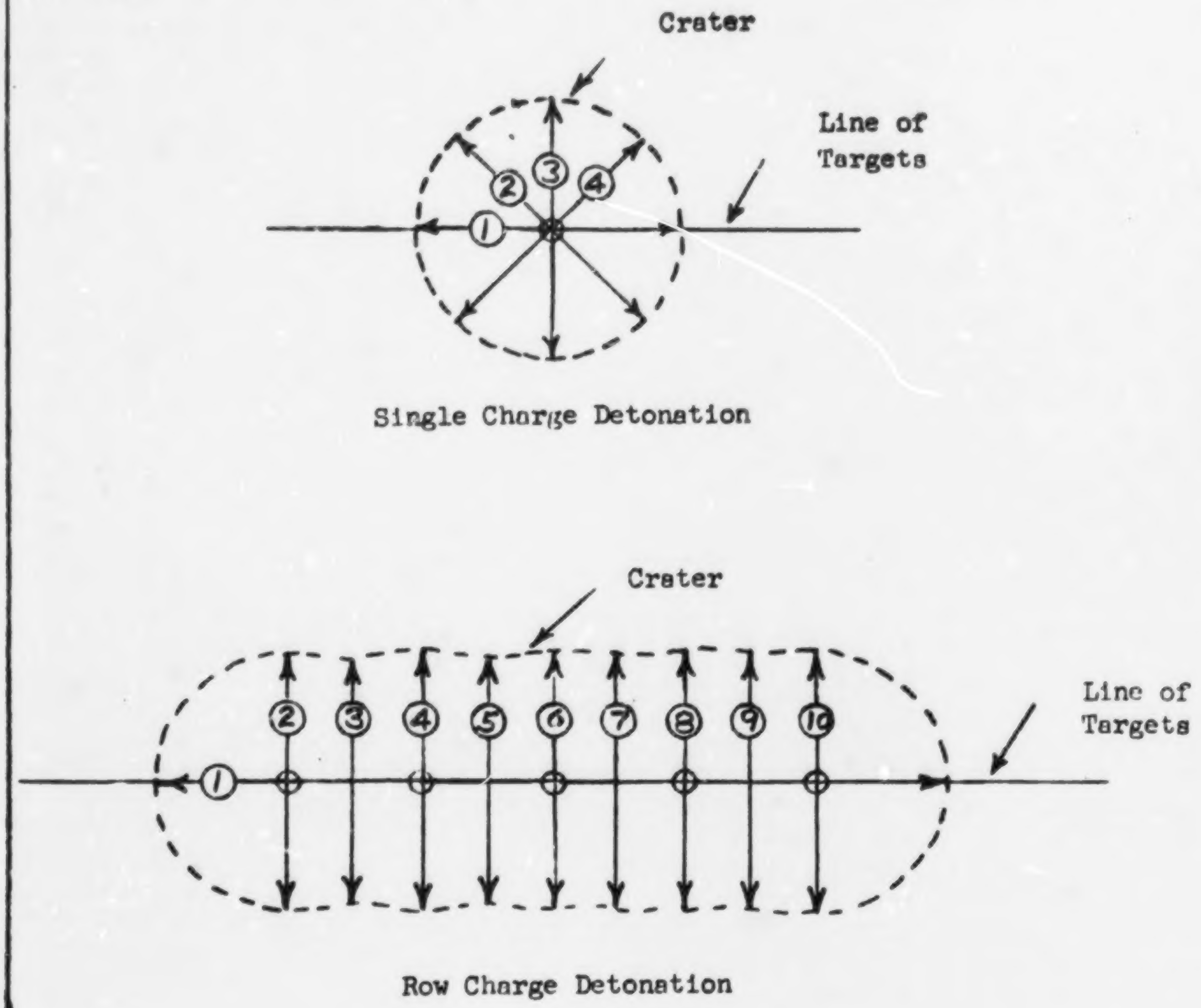

Crater
Line of Targets
1
2
3
4
Single Charge Detonation
Crater
Line of Targets
1
2
3
4
5
6
7
8
9
10
Row Charge Detonation

Figure 4.1 Crater Size Measurements

(Kurtz and others, 1966)

"Determination of R_{eb}. Continuous ejecta measurements were recorded as shown in Figure 4.2. Averages were calculated from these field measurements.

"Determination of R_{me}. Ranges to several outermost missiles were recorded as show in Figure 4.3. The largest value was selected as R_{me}.

"Results

"Crater Measurements. Tables 4.1 and 4.2 contain a summary of the crater measurements data...."

"Analysis and interpretation

"Single Charge Craters. The single charge crater radii reported in Table 4.1 are for charge weights from 127 1/2 to 940 lb of explosives. To compare the cratering effectiveness of the shots, all crater radii and depths of burst were normalized (by cube-root scaling) to 136 lb of C4, which was the average C4 charge weight with the exception of shot 31. Table 4.3 lists the scaled single charge crater radii and depths of burst.

"Cratering Calibration Series. Figure 4.19 shows the resulting curve for the single-charge cratering calibration shots conducted in the deepest water available.

"Energy Equivalent Yields. The relative ice cratering effectiveness of C4, ANFO, and TNT used in this report was based upon the approximate experimental heats of detonation of the explosives. Values of 1.20, 0.94, and 1.10 kcal/g were used for C4, ANFO, and TNT respectively. The use of these values means, for instance, that 100 lb of ANFO is as effective for ice cratering as 78.3 lb of C4....

"Bottom Reflection Series. Figure 4.20 shows the relative effectiveness of those shots detonated to determine the effect of reflections from the bottom of the lake. The effects of Shots FF1, FF2, and 31 are also shown. Shots 9, 20, 21, 22, 23, 24, and 25 all produced smaller craters indicating that no enhancement was gained by detonating 136 lb charges in water shallower than 33 to 52 feet.

"Yield Scaling. The results of Shot 31, as shown on Figure 4.20, indicates that scaling to larger yields might depart from the assumed cube root scaling. However, Figure 20 does not show the differences in appearance between the 940 and 136 lb craters nor the effect of scaling the ice thickness.

"All BREAKUP Shots were under essentially the same thickness of ice. The smaller yield shots did not contain the large 20 x 40 feet debris covered slabs found around the edge of the 940 lb crater. The slabs resulted from the extensive breaking associated with the larger charge.

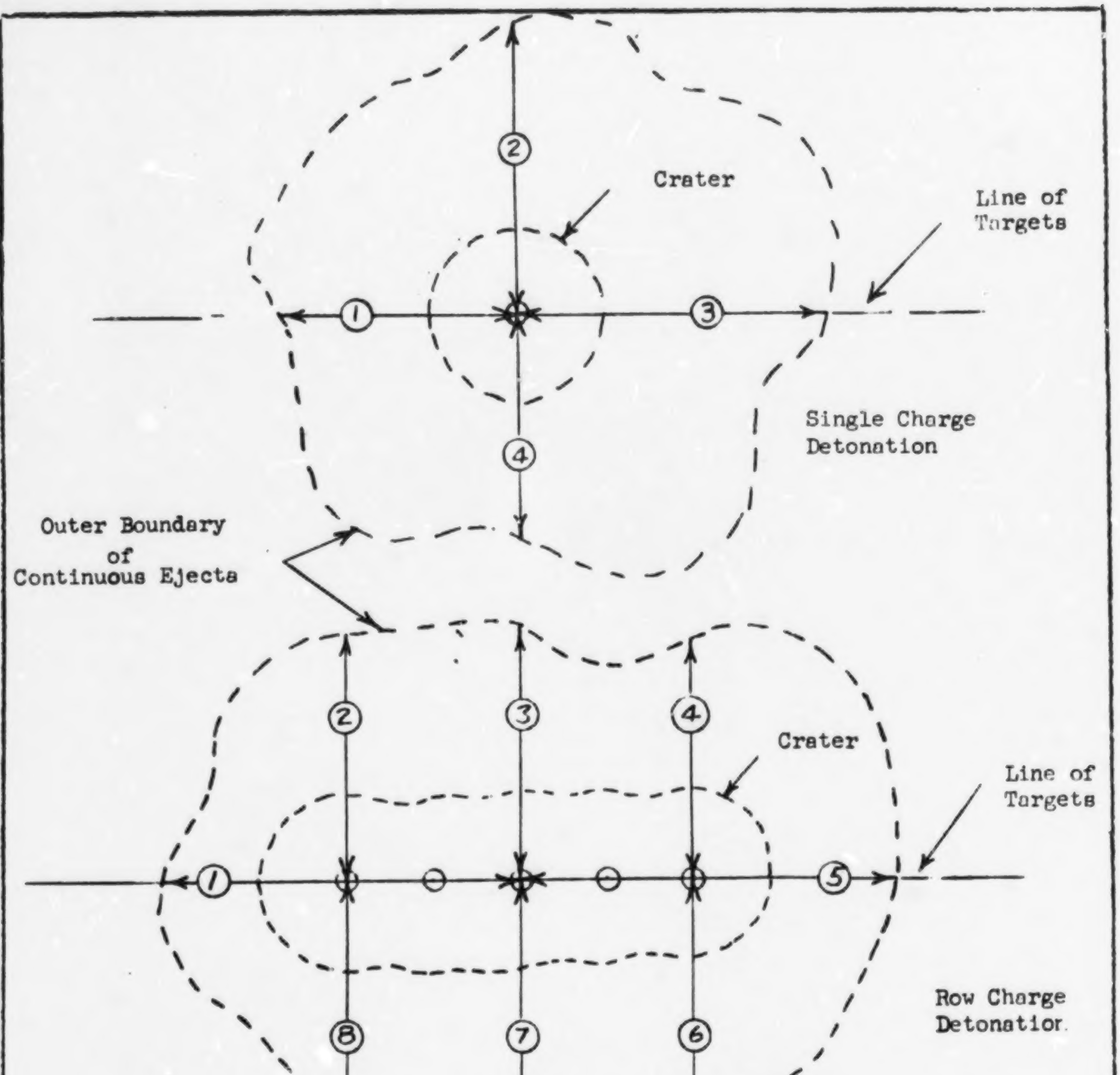
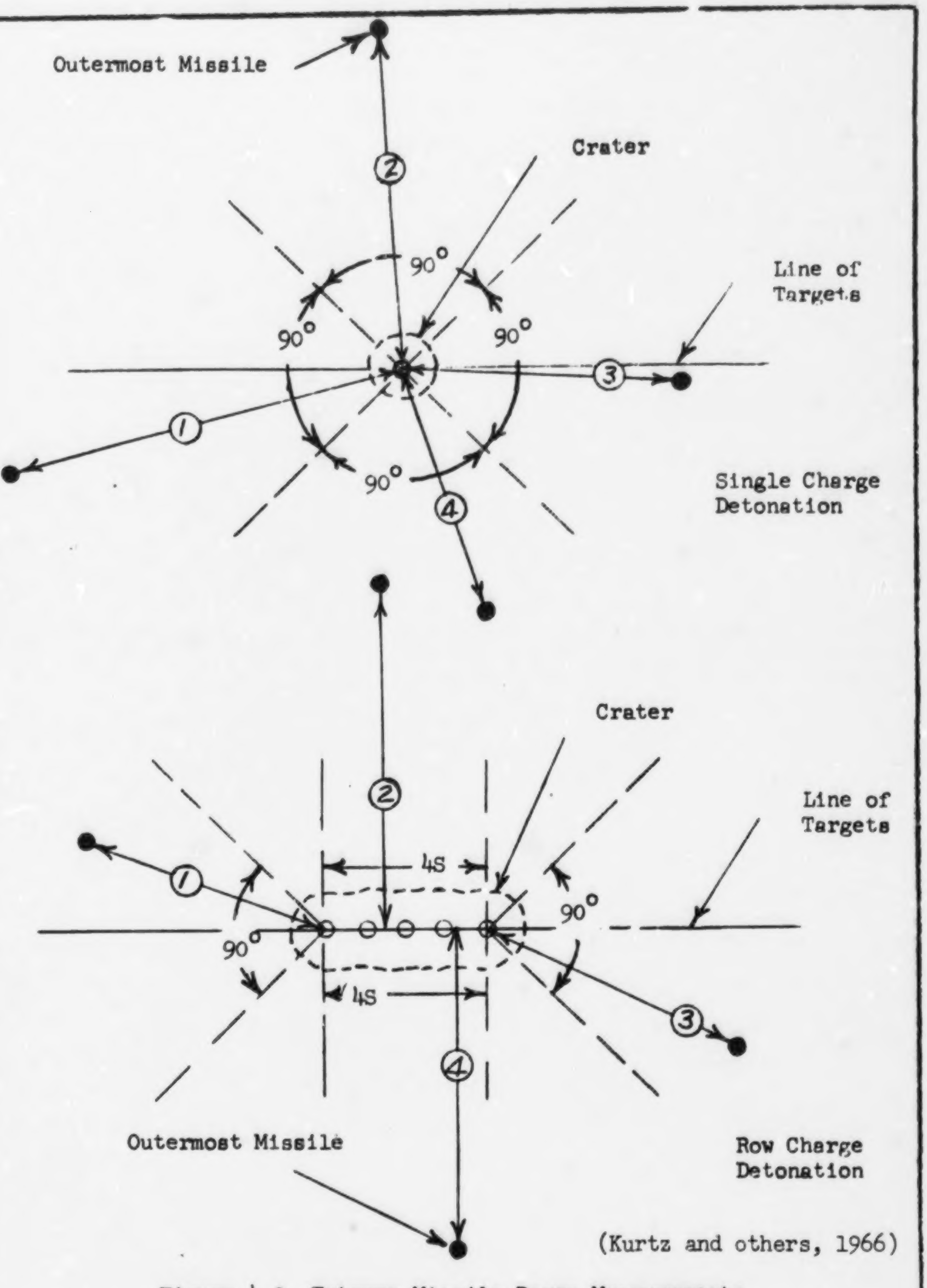

Crater
Line of Targets
Single Charge Detonation
Outer Boundary of Continuous Ejecta
Crater
Line of Targets
Row Charge Detonation
①
②
③
④
①
②
③
④
⑤
⑥
⑦
⑧

Figure 4.2 Outer Boundary of Continuous Ejecta Measurements (Kurtz and others, 1966)


Outermost Missile
Crater
Line of Targets
90°
90°
90°
90°
1
2
3
4
Single Charge Detonation
Crater
Line of Targets
4S
4S
90°
90°
1
2
3
4
Outermost Missile
Row Charge Detonation

(Kurtz and others, 1966)

Figure 4.3 Extreme Missile Range Measurements

TABLE 4.1 SINGLE-CHARGE CRATER MEASUREMENTS SUMMARY

Shot No.	Charge Weight	Ice Thick.	DOB^a	DOW^a	R_a^{b}	R_{cb}^{b}	R_{mc}^{c}
	Lbs of C4	In.	Ft.	Ft.	Ft.	Ft.	Ft.
1	$130\frac{1}{2}$	34.4	0	38	33.9	60.0	580
2	135	33.5	5	$43\frac{3}{4}$	33.6	69.3	208
3	130	35.8	10	$33\frac{3}{4}$	36.4	60.5	350
4	$141\frac{1}{2}$	29.8	15	36	35.3	54.8	189
5	130	31.6	20	$46\frac{1}{2}$	19.0	54.8	269
6	142	30.9	25	$48\frac{3}{4}$	24.2	60.0	260
7	138	33.0	$7\frac{1}{2}$	$42\frac{1}{3}$	35.7	59.0	263
8	$127\frac{1}{2}$	31.9	35	$51\frac{2}{3}$	22.8	55.8	257
9	$130\frac{1}{2}$	31.6	10	10	30.2	40.3	150
20	140	32.8	10	21	35.0	60.0	150
21	$134\frac{1}{2}$	31.0	15	20	26.3	47.8	205
22	$130\frac{1}{2}$	32.2	20	$19\frac{1}{2}$	15.4	31.5	195
23	135	31.4	10	30	35.4	40.0	257
24	$142\frac{1}{2}$	31.3	20	29	18.8	39.8	215
25	$140\frac{1}{2}$	36.1	30	30	8.5	30.2	75
31	940	34.5	19	$46\frac{1}{2}$	83.6	139.5	336
FF1	160(ANFO)	27.9	35	$51\frac{1}{2}$	23.7	55.9	163
FF2	150(TNT)	29^d	20	$51\frac{1}{2}$^{d}	27.0	67.5	242

a. Below bottom of ice layer
b. Average value
c. Maximum value
d. Approximate value

DOB - Depth of burst
DOW - Depth of water

(Ice thickness is the average around the shot point as reported by CRREL.)

(Kurtz and others, 1966)

TABLE 4.2 ROW-CHARGE CRATER MEASUREMENTS SUMMARY

(Kurtz and others, 1966)

Row	Shot No.	Charge Weight	Ice Thick.	Spacing	DOB[a]	DOW[a]	W_a[b]	L_a	R_{eb}[b] Side	R_{eb}[b] End	R_{me}[c] Side	R_{me}[c] End
		Lbs of C4	In.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
A	10-14	137	33.3	36	10	51	116.5	210	79	118.5	315	150
B	15-19	134½	32.4	54	10	49½	116.4	301.5	71.2	150	376	220
C	26-30	136⅗	33.0	72	10	49¼	135.0	362.1	62.5	193.5	331	337

a. Below bottom of ice layer
b. Average value
c. Maximum value

DOB - Depth of burst
DOW - Depth of water
L_a - Row crater length

(Ice thickness is the average around the shot point as reported by CRREL.)

TABLE 4.3 SCALED SINGLE CHARGE CRATER RADII AND DEPTHS OF BURST NORMALIZED TO 136 POUNDS OF C4 (Kurtz and others, 1966)

Shot No	Charge Weight (W)	Scaling Factor	DOB[a]	dob[b]	R_a [c]	r_a [d]
	lb of C4	$(W/136)^{1/3}$	ft	ft	ft	ft
1	136½	1.001	0	0	33.9	33.87
2	135	0.998	5	5.01	33.6	33.67
3	130	0.985	10	10.15	36.4	36.95
4	141½	1.013	15	14.81	35.3	34.85
5	130	0.985	20	20.30	19.0	19.29
6	142	1.014	25	24.65	24.2	23.87
7	138	1.005	7.5	7.46	35.7	35.52
8	127½	0.979	35	35.75	22.8	23.29
9	130½	0.986	10	10.14	30.2	30.63
20	140	1.010	10	9.90	35.0	34.65
21	134½	0.996	15	15.06	26.3	26.41
22	130½	0.986	20	20.28	15.4	15.62
23	135	0.998	10	10.02	35.4	35.47
24	142½	1.016	20	19.69	18.8	18.50
25	140½	1.011	30	29.67	8.5	8.41
31	940	1.905	19	9.97	83.6	43.88
FF1	125[e]	0.972	35	36.01	23.7	24.38
FF2	137½[f]	1.004	20	19.92	27.0	26.89

a. Below bottom of ice layer
DOB - Depth of burst

b. Scaled DOB

c. Average value

d. Scaled R_a

e. 160 lb ANFO = $160 \times \frac{0.94}{1.20}$ = 125 lb C4

f. 150 lb TNT = $150 \times \frac{1.10}{1.20}$ = 137½ lb C4

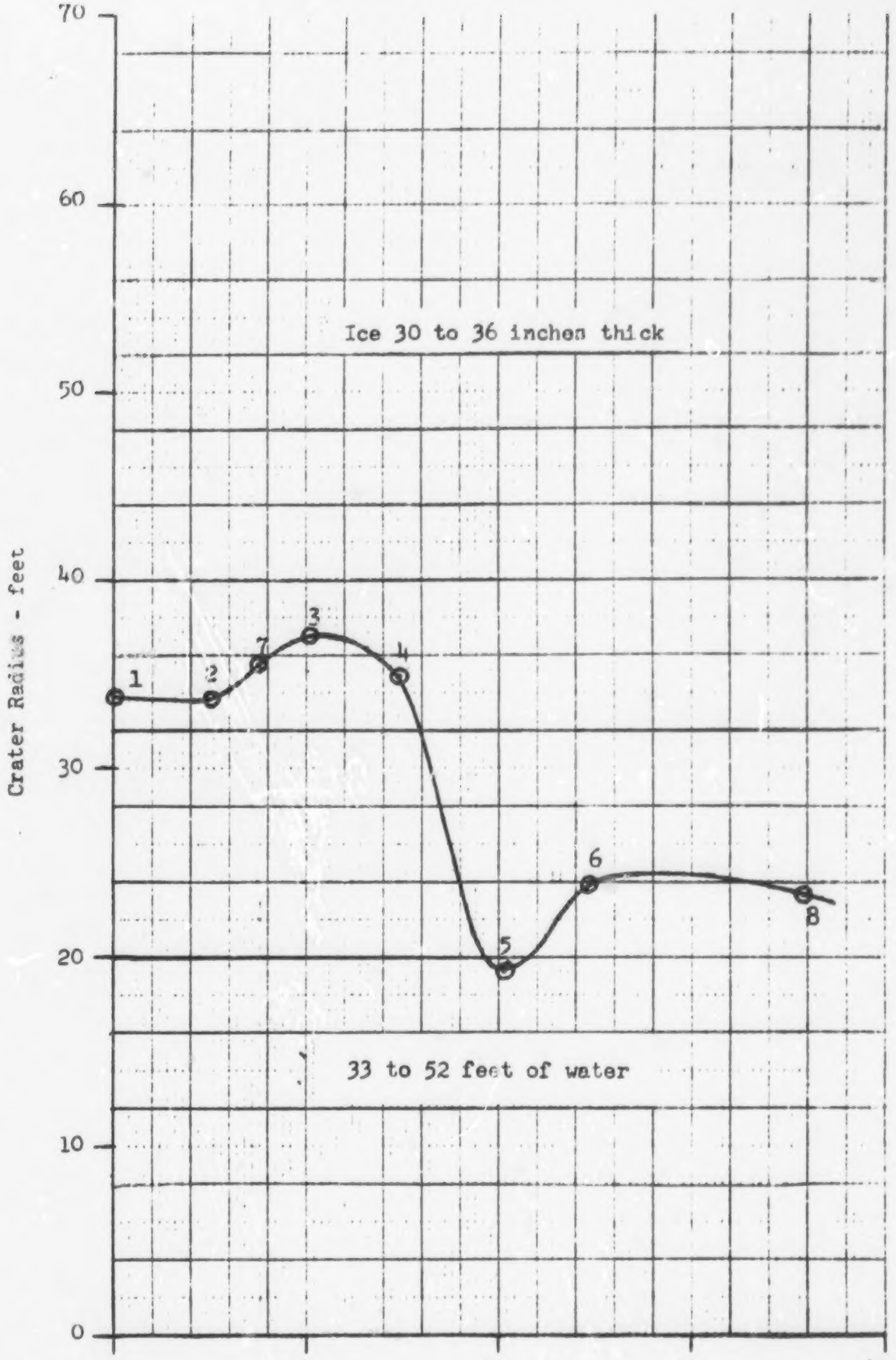


Figure 4.19 Single Charge Cratering Curve, 136 lbs C4.
(Kurtz and others, 1966)

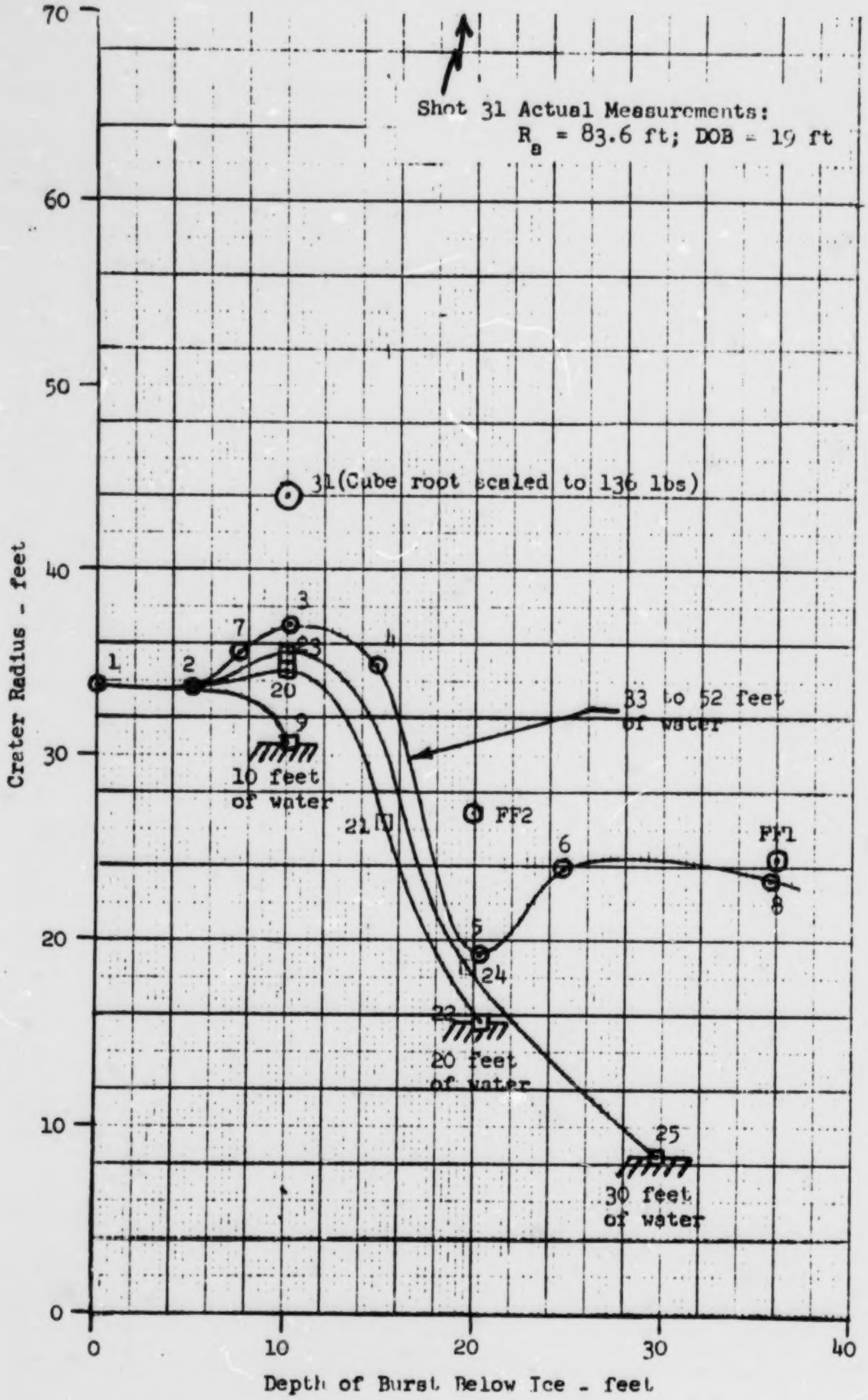


Figure 4.20 Comparison of Single-Charge Craters in Various Depths of Water, 136 lbs C4.

(Kurtz and others, 1966)

They were also noted in the row charge craters. The actual thickness of the ice layer which acted as a membrane could conceivably control the horizontal distance to which internally reflected shock waves could propagate cracks. The significance of internal reflection is unknown, however, and thus it is necessary to establish yield scaling from shot 31 data as compared to smaller 136 pound shots in the same thickness of ice.

"A comparison of R_a for shot 3 in 3 feet of ice with reports of optimum crater radius for smaller charges in thinner ice ... indicates that cube root scaling holds for yields of 1 to 1000 pounds if the ice thickness, t, is also scaled. The following relationships may be dervied to use the BREAKUP results for estimating the charge weight for optimum cratering in various thicknesses of ice:

$$\left(\frac{W}{136}\right)^{1/3} = \frac{t}{3} \text{ or } W^{1/3} = 1.71\ t \qquad (4.1)$$

$$\frac{R_a}{36.95} = \left(\frac{W}{136}\right)^{1/3} \text{ or } R_a = 7.19\ W^{1/3} \qquad (4.2)$$

$$\frac{DOB}{10.15} = \left(\frac{W}{136}\right)^{1/3} \text{ or } DOB = 1.98\ W^{1/3} \qquad (4.3)$$

where the units are feet and pounds of C4. Heats of detonation may be used to determine energy equivalence of other explosives."

"As in the BREAKUP experiments, if the ice thickness is held constant and the yield varied, then different results are to be expected than cube root scaling would indicate. The results of shot 31 can be used to evaluate the effect of yield on ice of constant thickness. As shown on Figure 4.20, the scaling factor needed for agreement between the 136 pound curve and shot 31 is $\left(\frac{940}{136}\right)^n = \left(\frac{83.6}{36.95}\right) = 2.26$. This corresponds to a scaling power (n) of approximately 1/2.4 rather than 1/3 for 36 inches of ice. The same scaling factor was also noted in recent tests to (sic) CRREL with various yields under 20 inches of ice on the Mississippi near Elk River, Minnesota (Frankenstein, 1966-private communication). Assuming, therefore, that it is valid over a wider range, the following shows the relationship between the optimum crater radius R_a as determined by equation 4.2 for yield W and the adjusted radius for a different adjusted yield, Y, under the same ice thickness:

$$\frac{R_{adj}}{R_a} = \left(\frac{Y}{W}\right)^{1/2.4} \text{ or } R_{adj} = R_a \left(\frac{Y}{W}\right)^{1/2.4} \qquad (4.4)$$

"... Using the optimum R_a and W as the 'model', equation 4.4 can be used to adjust the model for distortions created by not scaling the ice thickness. This might arise when a given crater radius is required and the ice thickness is fixed. Equation 4.4 is re-written as follows to determine the required yield:

$$Y_{required} = W_{model} \left(\frac{R_{required}}{R_{a\ model}} \right)^{2.4} \quad \ldots \qquad (4.5)$$

"To scale to very large yields the commonly used 1/3 and 1/3.4 yield scaling exponents may be used for approximations. Figure 1.6 shows the relative crater size normalized to 1 kt so that the results may be compared to craters in other media.

"Row Charge Craters. For a consistent comparison of the row and single charge data, the row widths and row depths of burst shown in Table 4.2 were also cube root scaled to 136 lb of C4. The resulting dimensions are shown in Table 4.4 and plotted with the single charge cratering curve on Figure 4.21. Figure 4.22 compares the rows with single-charge craters.

"These results show that a row charge detonation produces a much larger average crater half-width than does a single charge detonation. The average half-widths of rows A, B, and C (Table 4.4) were 57%, 58%, and 82%, respectively, larger than the crater radius produced by a single charge of the same yield as the average individual charges of the row and placed at the same depth of burst as that of the charges of the row.

"Care must be exercised when drawing conclusions based upon the enhancement of row crater size because the row crater contained large (greater than 20 feet) slabs, whereas the single charge craters did not. If 20 feet is subtractedfrom the half-widths of Table 4.4 to allow for the presence of slabs, the percentage increases become 3%, 4%, and 28% for rows A, B, and C, respectively.

"The measurements of each row do not indicate the formation of cusps at locations between the charges. This indicates that charges spaced at intervals even greater than 2.0 R_a may also result in a linear row. However, if cusps result from greater spacing, allowance may have to be made in practical applications where minimum width could be important, such as clearing ship channels.

"It is significant that while a man could not cross rows A and B on foot immediately after detonation, he could, with caution, walk across row C. Spacing the charges further than 2.0 R_a would probably increase the postshot trafficability in still water....

TABLE 4.4 SCALED ROW CHARGE CRATER WIDTHS AND DEPTHS OF BURST NORMALIZED TO 136 POUNDS OF C4
(Kurtz and others, 1966)

Row	Charge Nos.	Charge Weight (W)	Spacing	Scaling Factor	DOB[a]	dob[b]	W_a[c]	w_a[d]	$\frac{w_a}{2}$
		lbs of C4	ft	$(W/136)^{1/3}$	ft	ft	ft	ft	ft
A	10 - 14	137	36	1.002	10	9.98	116.5	116.27	58.14
B	15 - 19	$134\frac{1}{4}$	54	0.996	10	10.04	116.4	116.87	58.44
C	26 - 30	$136\frac{3}{5}$	72	1.001	10	9.99	135.0	134.27	67.44

a. Below bottom of ice layer

b. Scaled DOB

c. Average value

d. Scaled W_a

DOB = Depth of Burst

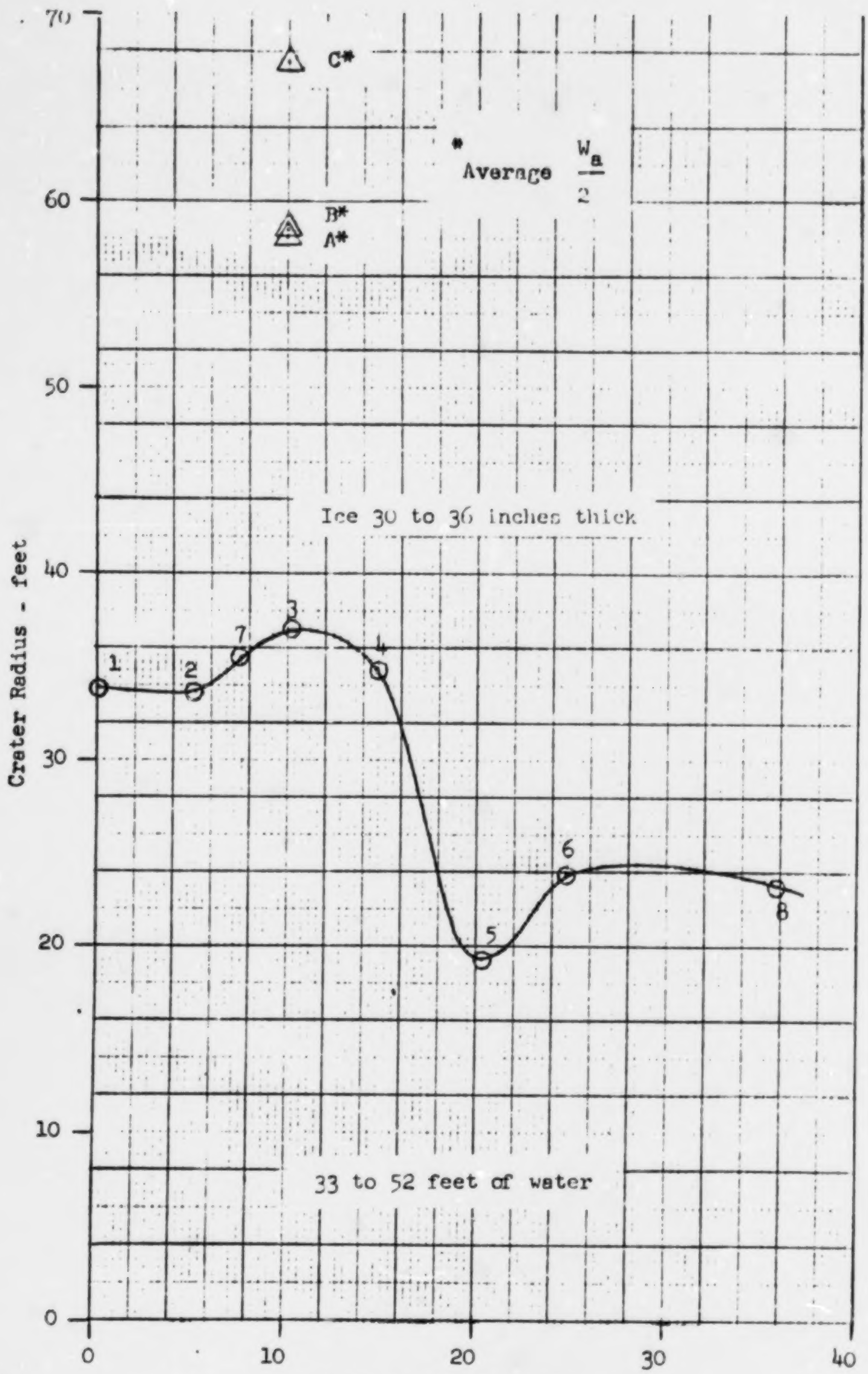


Figure 4.21 **Comparison of Single- and Row-Charge Craters, 136 lbs C4.**

(Kurtz and others, 1966)

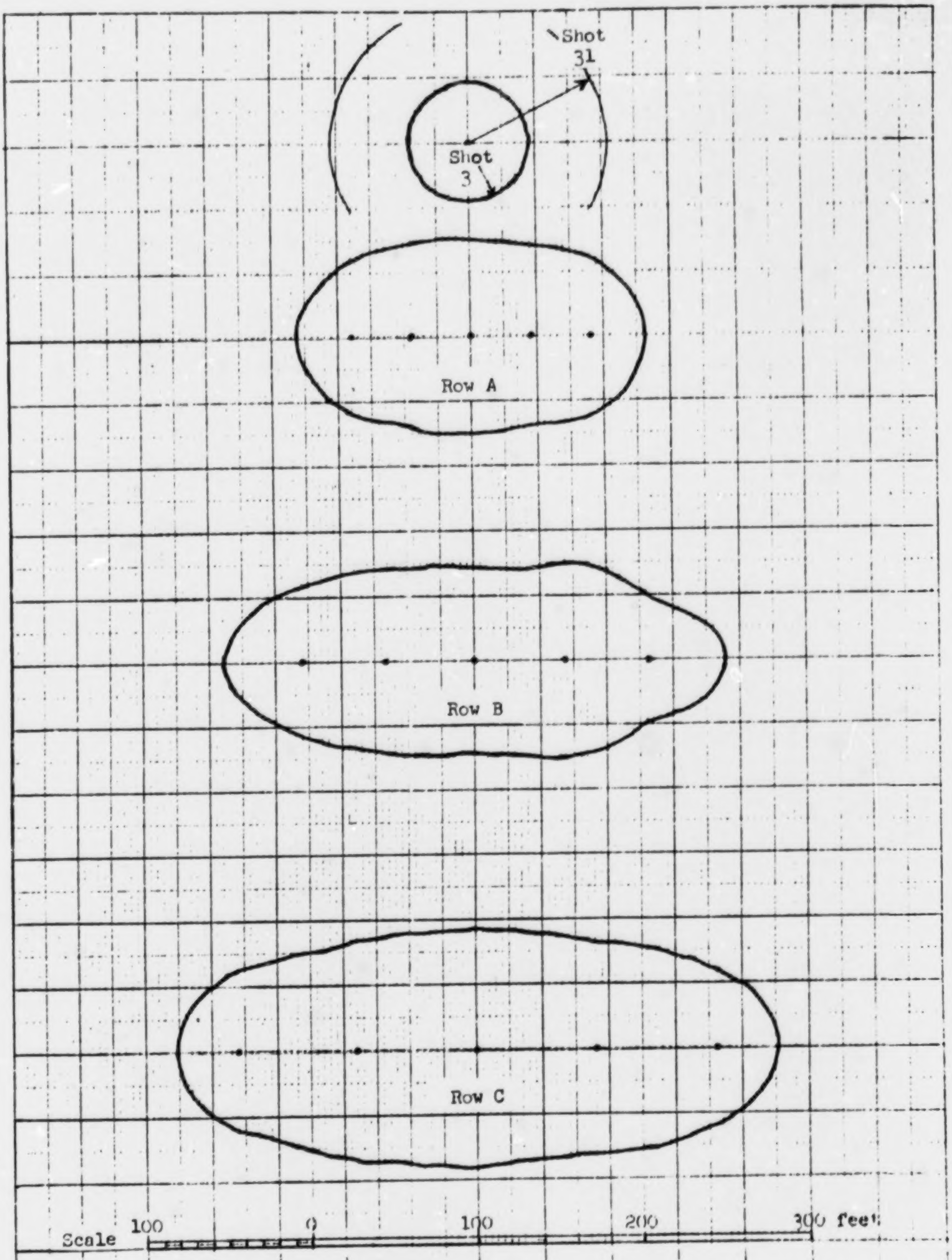

Shot
31
Shot
3
Row A
Row B
Row C
Scale
100
0
100
200
300 feet

Figure 4.22 Comparative Crater Dimensions.

(Kurtz and others, 1966)

"Crater Appearance. The craters formed for all shots except 31 were completely covered with debris consisting of ice fragments and snow. (Shot 31 exposed a significant area of water surface.) The ejected ice and water made the surface of the surrounding area rough and difficult to traverse. However, in approximately one day, the entire area including the crater was frozen deep enough that foot traffic could easily cross the ejecta and crater. Because of the rough and broken nature of the surface covering, vehicles (when the area would support them) would have difficulty in making a crossing through the craters.

"The size of the largest blocks or slabs of ice found in the single-charge craters seldom exceeded 3 or 4 feet in diameter. The maximum size for the rows and the 940 lb charge, however, were as large as 20 x 40 feet....

"Surface motion phenomena

"Results and discussion

"Displacement and Velocity Histories of Shots 1, 3, and 4.

"Shot 1. Figure 5.2 shows the vertical velocity vs. time plot of the SGZ target of shot 1. On this shot the center of the charge was at the bottom edge of the ice. All targets within the crater were obscured by the immediate vent of this detonation; therefore, it was not possible to plot mound growth as shown by target displacements. The mound peak reached a peak velocity of 930 feet per second in the first few milliseconds, held this velocity until about 20 msec, and then began decelerating. Because much of the material at the peak of the mound was fine ice and snow, air drag caused the deceleration to be considerably greater than would result from free fall alone. This mound reached a height of about 130 feet at about 200 msec.

"Shot 3. Table 5.2 and Figure 5.3 and 5.4 show the data from shot 3. Shot 3 had a depth of burst of 10 feet (below the bottom edge of the ice). This was determined to be the optimum depth for crater production. Table 5.2 presents the surface motion data obtained from shot 3. The velocity history curves on this shot would rise to a peak just after 50 msec and would remain almost constant at that peak until almost 500 msec. Therefore, the velocities shown are the averaged values over this interval.

"The angle Θ is the angle between the vertical and the radial from shot point through the initial target position. The angle Ø is the angle between the vertical and the early target directional vector (during the first 100 msec). The lines representing each of these angles are shown on Figure 5.3.

"Figure 5.3 shows the mound shape at 88, 170, and 846 msec, as well as the SGZ target's position at intermediate times. The mound reached a peak of about 75 feet at 1200 msec.

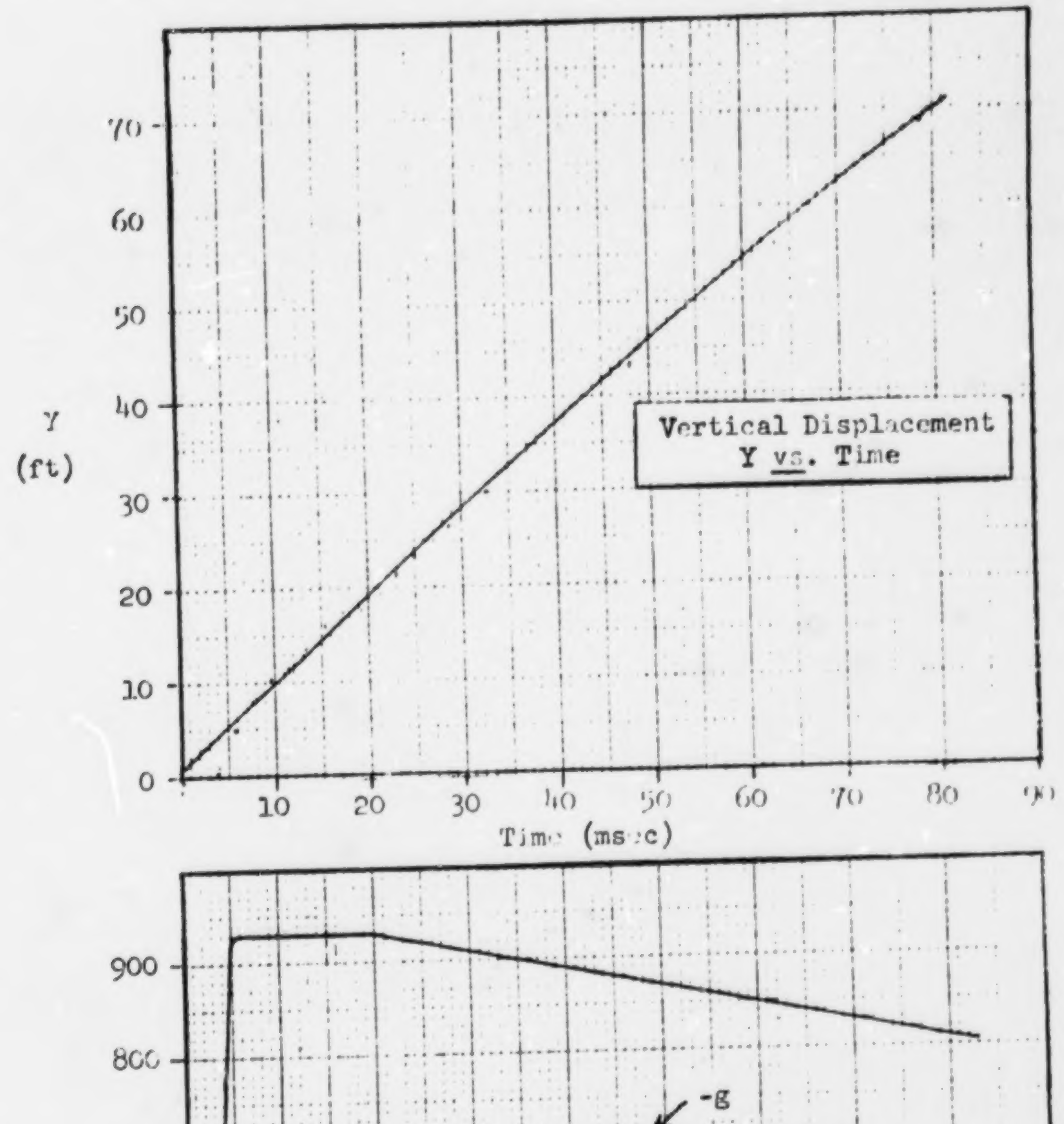


Figure 5.2
BREAKUP Shot 1
DOB = 0 ft; DOW = 38 ft
SGZ Target
0 to 90 msec

(Kurtz and others, 1966)

TABLE 5.2 BREAKUP 3 TARGET VELOCITIES - 130 lbs C4; DOB = 10 ft (Optimum)

All velocities shown are characteristic velocities averaged between 50 and 500 msec.

Target No	Position	$\dot{X}$	$\dot{Y}$	$(\dot{X}^2 + \dot{Y}^2)^{\frac{1}{2}}$	θ	ϕ
1	-19.5	-	-	-	56.8°	31.0°
2	-10.4	-39	31	50	37.8°	34.5°
3	0	+1	84	84	-	-
4	13.1	+23	22	32	45.0°	30.2°
5	20.6	+20	3	20	57.7°	34.4°
6	29.5	+4	-2	4	66.2°	41.0°

(Kurtz and others, 1966)

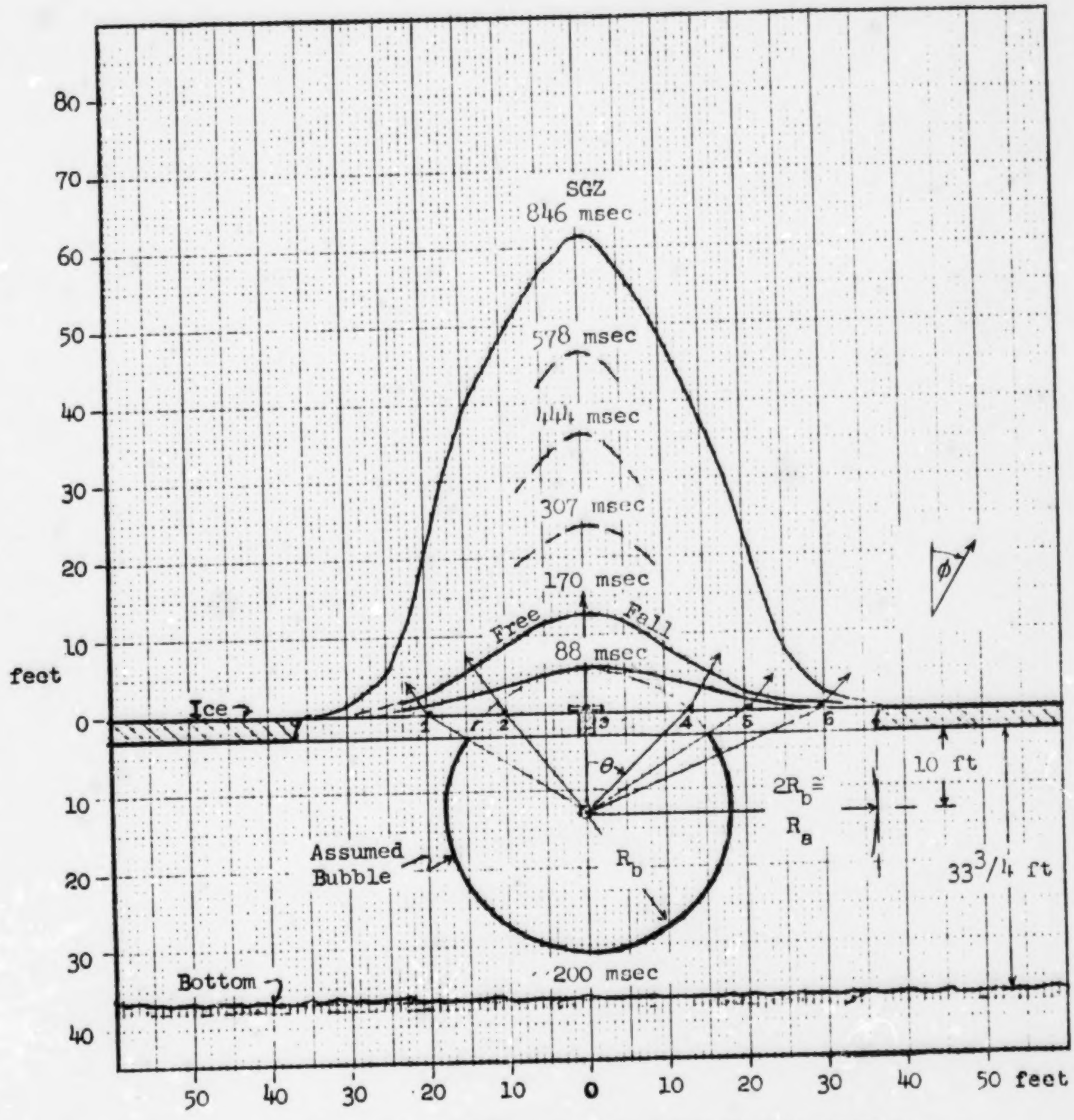


Figure 5.3 BREAKUP Shot 3 Target Displacements.
(Kurtz and others, 1966)

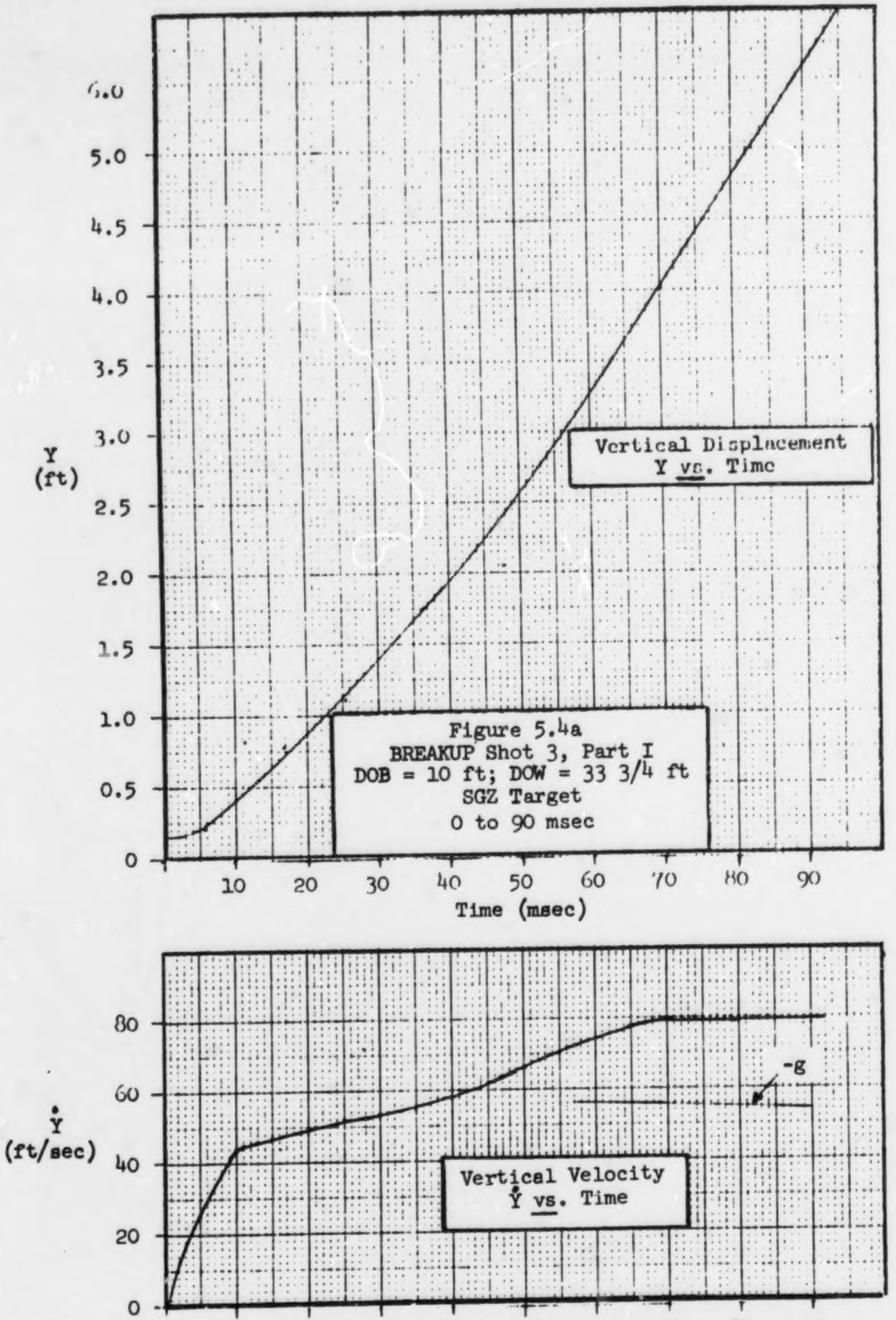


Figure 5.4a
BREAKUP Shot 3, Part I
DOB = 10 ft; DOW = 33 3/4 ft
SGZ Target
0 to 90 msec

(Kurtz and others, 1966)

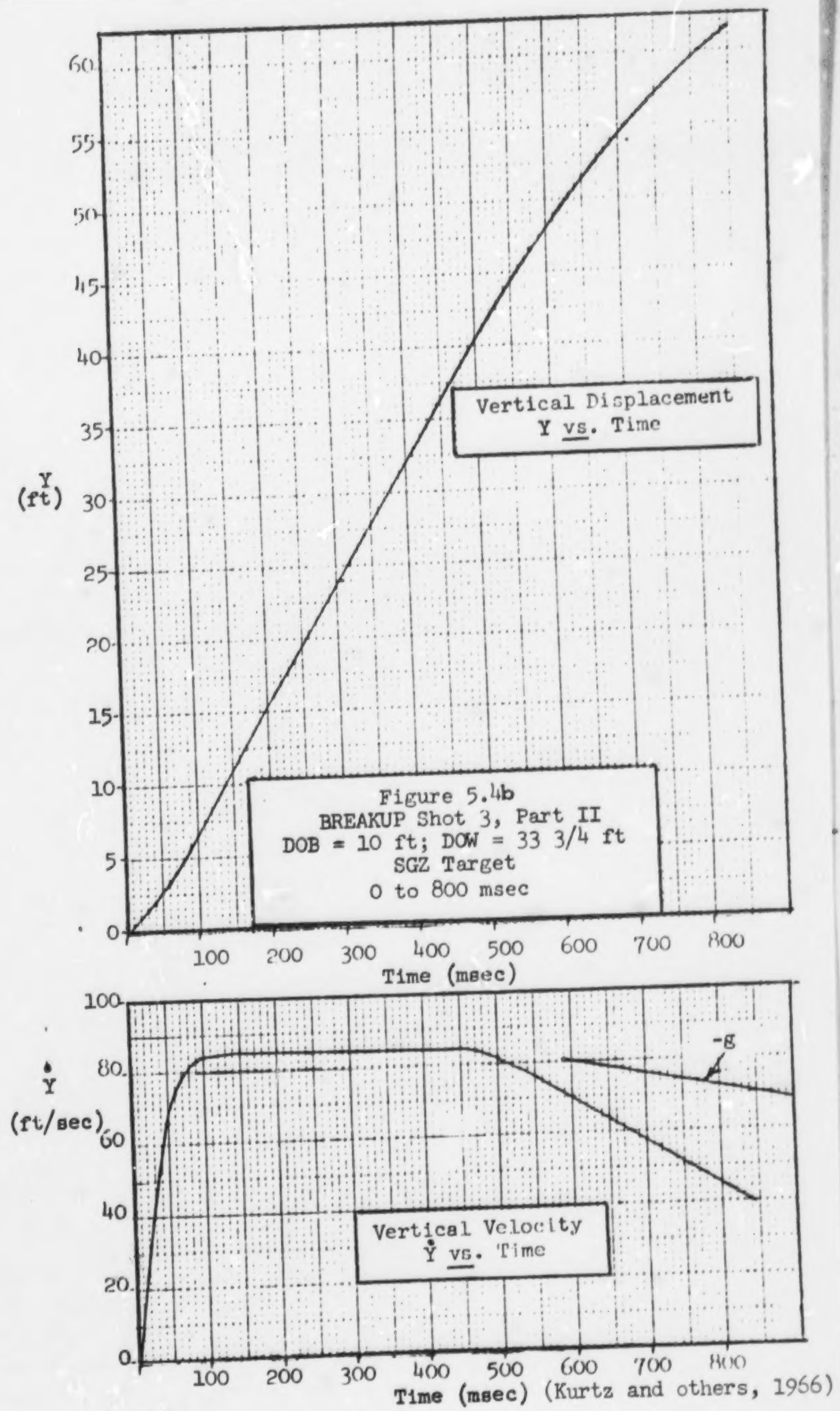


Figure 5.4b
BREAKUP Shot 3, Part II
DOB = 10 ft; DOW = 33 3/4 ft
SGZ Target
0 to 800 msec

(Kurtz and others, 1966)

"Figure 5.4 shows the SGZ vertical displacement and velocity vs. time plots. The mound peak achieved a maximum velocity of 85 feet per second at about 100 msec, held this peak until almost 500 msec, and then began deceleration. As was the case with shot 1, the deceleration is much greater than from free fall because of the fineness of the particles.

"Shot 4. Table 5.3 and Figures 5.5 and 5.6 present the surface motion data from shot 4, whose depth of burst was 15 feet.... Figure 5.5 shows the lines whose angles from the vertical are the angles θ and ϕ. Also shown are the mound shapes at 73, 212, and 462 msec.

"Figure 5.6 shows a Y vs time plot for 0 through 130 msec and for 0 through 400 msec, and a Y velocity vs time for 0 through 140 msec. On the Y velocity plot can be seen two distinct phases of surface motion. The first phase (from 0 to 20 msec) peaked at about 35 feet per second. The second phase (from 45 to 80msec) peaked 97 feet per second. These phases of motion are discussed in the following sections."

"Distinctive Phases of Surface Motion.

"Phase One. As the gas bubble expanded, the overlying ice sheet bulged upward, usually from one to three feet for the 125-lb shots. The ice sheet remained cohesive and the targets rode in their positions on the ice. Since snow was on the ice for most of the shots, it was impossible to tell if any cracks formed during this phase. This phase had radically different durations depending upon the DOB. For the charges 10 feet or less below the bottom of the ice, the gas bubble vented immediately through the emplacement hole and Phase One was almost undetectable. For the 30 and 35-foot shots, Phase One lasted over 1220 msec. In fact, for these deeper shots, it was evident that the ice sheet was moving downward long before the advent of Phase Two. From this, it is assumed that the ice sheet was not broken up by the Phase One movement and that the ice sheet rebounded downward under tension before the gas bubble vented on the deeper shots."

"... Except for the two shallowest shots analyzed (1 and 3) no movement was detected before 15 milliseconds. No high acceleration phase within the first ten milliseconds could be detected for any of the detonations.... Phase One often did not reach its peak velocity until after 100 milliseconds which means that the ice surface was accelerated for a long period after the end of any spall....

"Phase Two. Phase Two is the venting of the gas bubble through the ice sheet. The time at which this phase began varied from immediately for the shot at the bottom of the ice to more than 1200 msec for the 35-foot shots. This vent carried water, ice, and snow up with it. Large blocks of ice could be seen rising with the vent, but the uppermost particles were always very fine, because after achieving freefall, they invariably decelerated much more than from freefall. Therefore, air drag had a great effect upon them. The base of the vent was usually 20 to 30

TABLE 5.3 BREAKUP 4 TARGET VELOCITIES - 141 1/2 lbs C4; DOB = 15 ft

All velocities shown are characteristic velocities averaged between 60 and 300 ms.

Target No	Position	$\dot{X}$	$\dot{Y}$	$(\dot{X}^2 + \dot{Y}^2)^{\frac{1}{2}}$	θ	ϕ
1	-36.6'	-1	7	7	63.6°	19.5°
2	-27.3'	-2	13	13	56.2°	18.0°
3	-19.3'	-10	22	24	47.2°	17.5°
4	-10.9'	-18	51	54	31.2°	10.5°
5	0	0	97	97	-	-
6	+10.3'	14	59	61	30.2°	13.0°
7	+17.6'	9	35	36	44.6°	15.6°
8	+26.0'	3	11	11	55.2°	21.3°
9	+35.4'	-1	5	25	63.0°	23.1°
10	+52.3'	0	1	1	71.1°	-

(Kurtz and others, 1966)

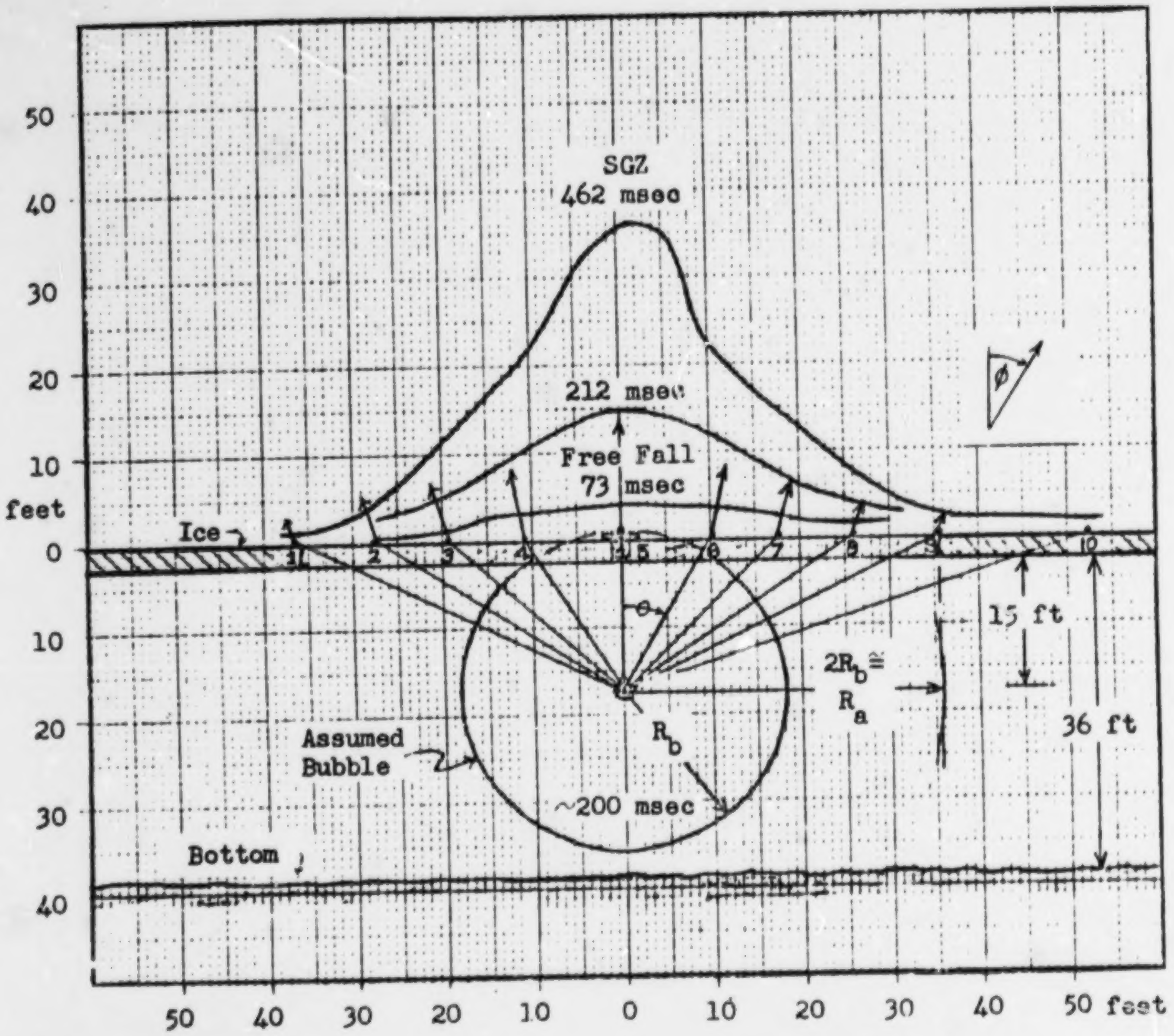


Figure 5.5 BREAKUP Shot 4 Target Displacements.
(Kurtz and others, 1966)

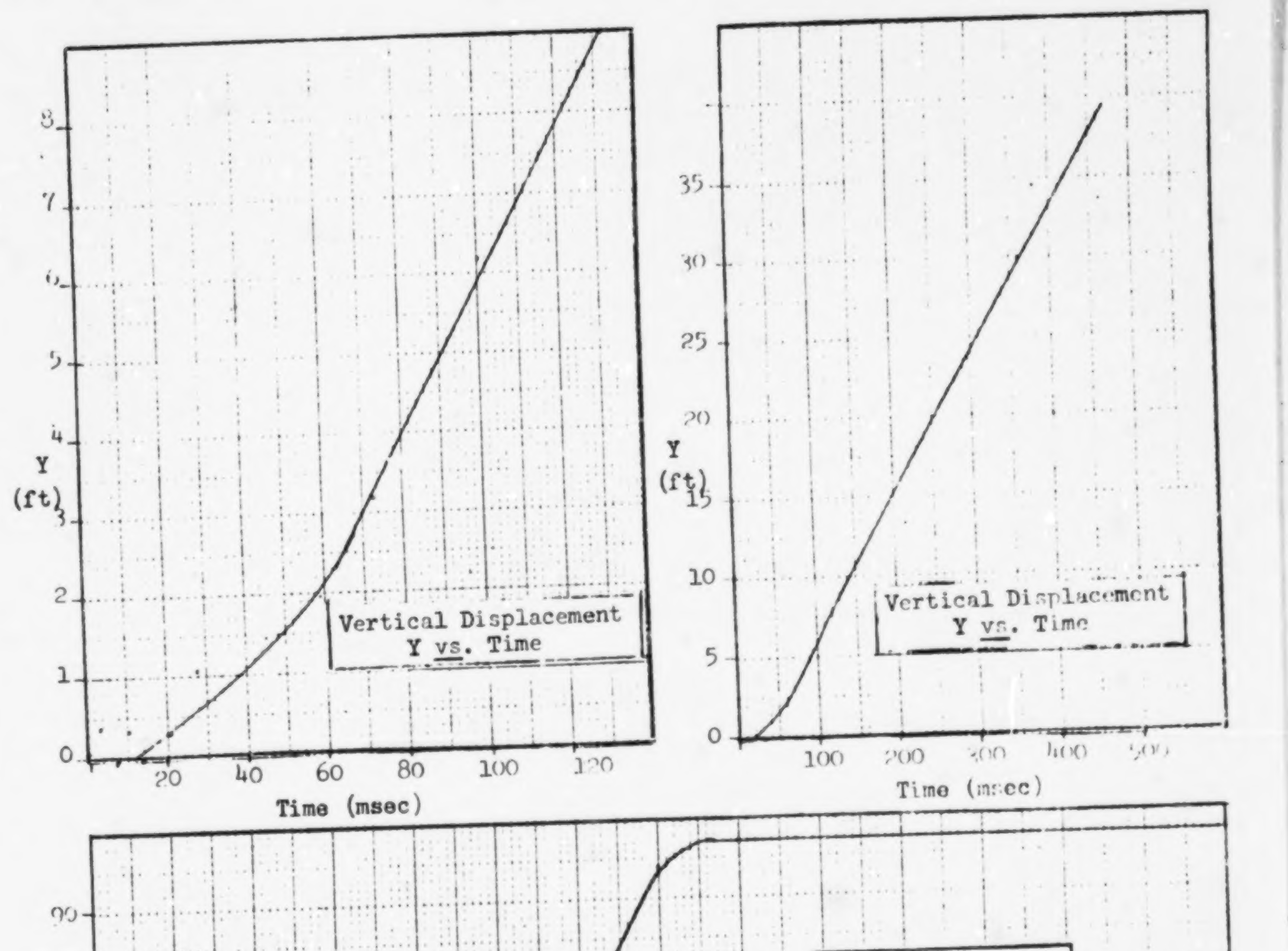
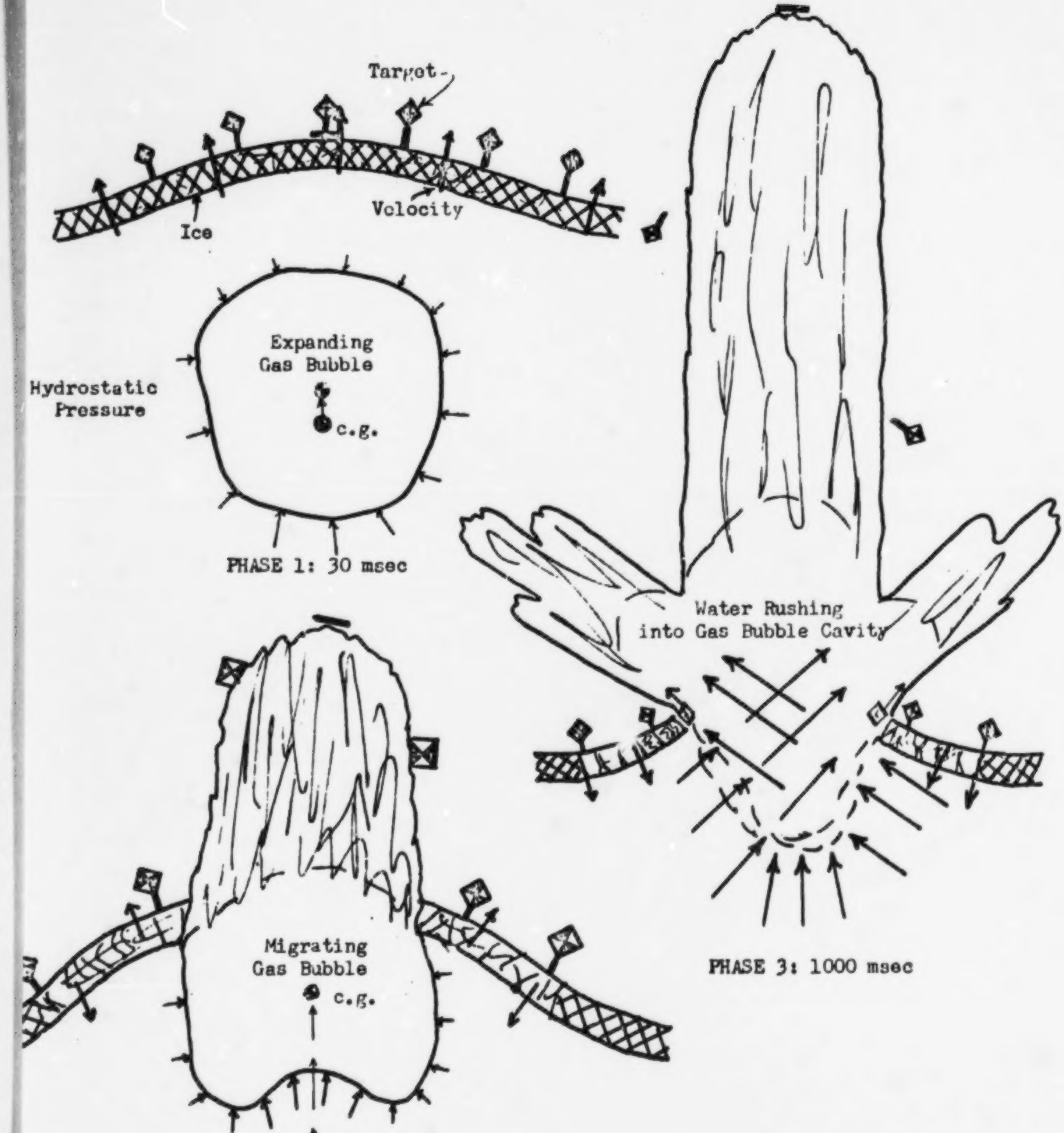


Figure 5.6
BREAKUP Shot 4
DOB = 15 ft; DOW = 36 ft
SGZ Target
0 to 140 msec; 0 to 400 msec

(Kurtz and others, 1966)



PHASE 1: 30 msec

PHASE 2: 60 to 600 msec

PHASE 3: 1000 msec

Target
Velocity
Ice
Expanding Gas Bubble
Hydrostatic Pressure
c.g.
Migrating Gas Bubble
c.g.
Water Rushing into Gas Bubble Cavity

Figure 5.7 Typical BREAKUP Motion Phases - DOB = 15 f
(Kurtz and others, 1966)

feet wide at its maximum and its height varied from about 40 feet for the 35-foot DOB shots to 130 feet for the 0 foot DOB shot. On some shots, especially the rows, the log used to secure the charge in place ... could be seen at the top of the vent at late time, usually just when the maximum height was reached. The velocity of Phase Two varied with DOB, the shallow shots having a higher vent velocity than the deeper ones.

"The advent of Phase Two was very difficult to determine for shots shallower than 20 feet. The rise of the mound during Phase One was relatively rapid, and Phase Two began while the mound was still accelerating under the influence of Phase One....

"Phase Three. Phase Three was a low-angle vent of water and vapor caused by the rush of the water into the cavity vacated by the gas bubble as it vented. This vent occurred at a late time, usually about one second after detonation."

"Table 5.4 presents the data on the three phases of motion for selected shots in Operation BREAKUP.

"Mud Surge. On several of the deepest shots, at about 1.5 or 2 seconds after the detonation, the water 'boiled' up at the surface violently, usually surging outside the crater. The water was very muddy at this point and deposited mud around the edge of the crater by this action. It appeared to be a second water surge, similar to Phase Two, but having much less force.

"Charges Detonated In Rows.

"... The surface motion of each row appeared identical, therefore the three rows will not be discussed separately....

"Each charge in each row appeared to act independently. Phase One of the motion could not be differentiated from Phase Two due to the reasons described above for shots less than 15 feet deep. There were five distinct plumes in each row and five distinct third phases of motion. The third phase of motion did overlap on adjacent charges, but only after venting through the ice sheet.

"Since each gas bubble vented at some time prior to 50 msec, and the ice surface between adjacent charges was in place long after this time, there was obviously no coalescence of gas bubbles of adjacent charges beneath the ice.

"The maximum height of material was about 100 feet. The third phase vent began at about 1 second for each row."

TABLE 5.4 SURFACE MOTION CHARACTERISTICS, 136 POUND CHARGES OF C4. (Kurtz and others, 1966)

Shot No	DOB (ft)	Depth of Water (ft)	V Max Phase 1 (ft/sec)	Time of Vent Phase 2 (msec)	V Max Phase 2 (ft/sec)	Max Height of Material (ft)	Time of Vent Phase 3 (msec)
1	0	38	-	1	930	~130	-
3	10	34	-	<50	85	~ 75	1100
4	15	36	45	50	97	~ 90	960
5	20	47	~ 25	~730	~ 122	~ 70	~1000
6	25	49	~ 19	~780	~ 48	~ 40	~1000
8	35	52	-	~870	-	~ 30	~1200
9	10	10	-	<50	~137	~ 75	~1000
20	10	21	-	<50	~110	~ 70	~1000
21	15	20	-	<50	~ 48	~ 50	-
22	20	20	-	<50	~ 39	~ 25	-
23	10	30	-	<50	~ 88	~ 70	-
24	20	30	~ 28	~ 1040	~105	~ 50	~ 1040
25	30	30	~ 16	~ 1290	~ 18	~ 30	~ 1290
31*	19	47	-	< 50	122	~110	~1500
Row A	10	51	-	< 50	55	~100	~1100
Row B	10	50	-	< 50	75	~100	~ 950
Row C	10	49	-	< 50	70	~100	~1000

* 940 pound charge
Indicates approximated values

"Engineering properties

"Introduction

"... The purpose of this program was to document those properties of the ice and snow that might be needed to interpret the measurements.... A secondary objective was to establish the ability of the refrozen hole to support a man or vehicle and to measure the extent of cracking. This latter information would be useful in planning operations associated with removal of ice jams...."

"Results

"Figure 6.10 is a plot of the average daily temperature for the projected period. The sudden drop in temperature on 17 February is also evident on the snow temperature curves....

"Ice Properties. The snow-ice had an average density of 0.899 gm/cm^3 and the clear ice 0.915 gm/cm^3. The snow-ice average 11.6 cm in depth and occurred on top of the clear ice. Average total ice thickness is shown in Table 6.1.

"The low temperatures made it very difficult and almost impossible to conduct beam tests to determine flexural strength....

"Crack Data. Table 6.2 lists the crack information for each shot....

"It is obvious that more cracks were present after the shots but with the amount of snow present on the ice surface, they were difficult to find....

"There were two types of cracks that formed - circumferential and radial. The circumferential cracks circle the failure hole at different distances away from its edge. These are the main or major type of cracks while the radial ones are the minor type. The radial cracks form in a radial direction outward from the center of the crater hole.

"If the craters had been formed in river ice subjected to currents, the cracks would facilitate downstream displacement of the cracked and cratered ice. An open water area could be maintained under these conditions.

"The engineering properties data indicate that all craters were formed in essentially the same material and there should be few anomalies in the data from disturbances from prior adjacent detonations.

"Refreeze Data. Table 6.3 lists the refreeze history of the crater holes for which this measurement was taken.

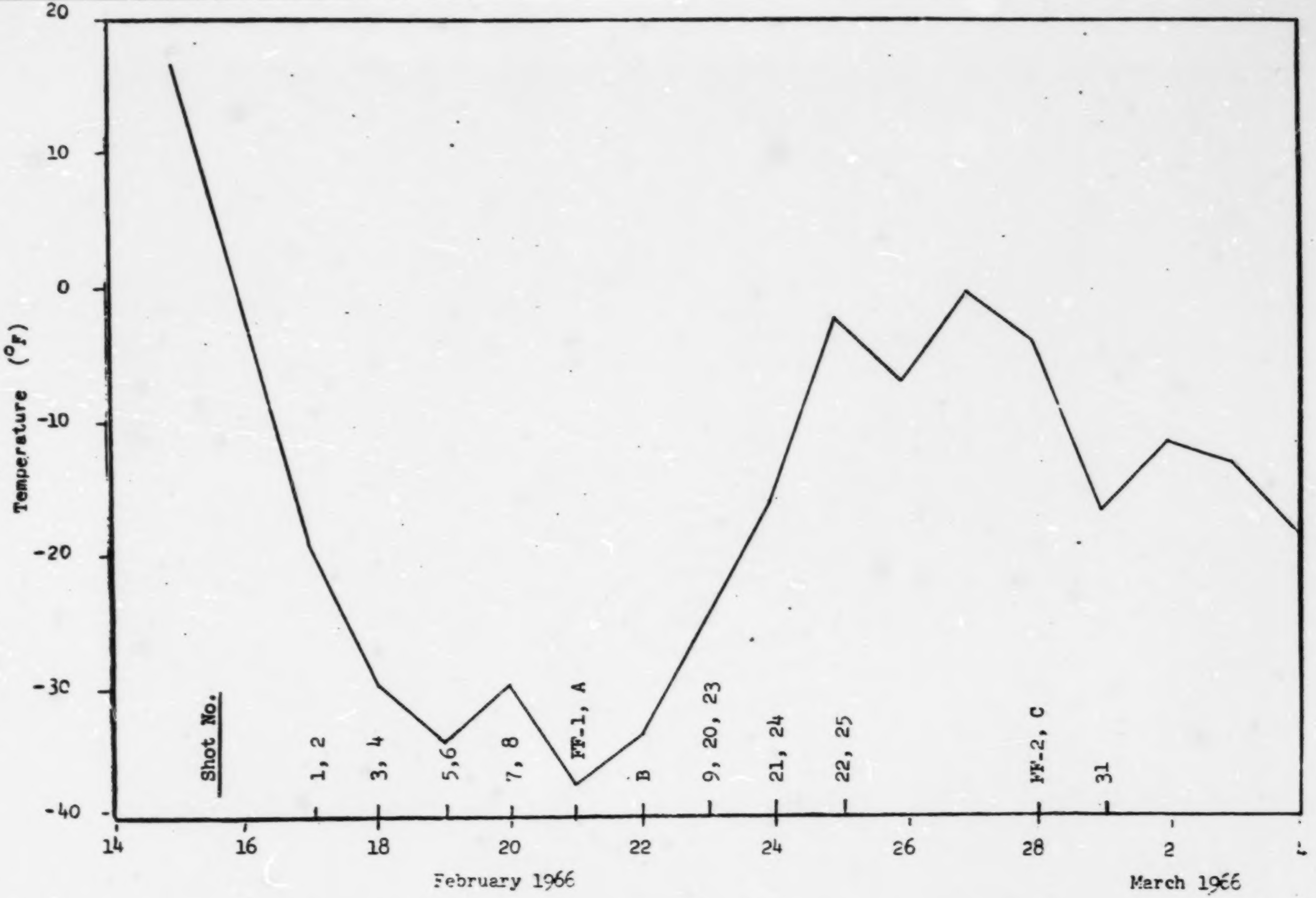


Figure 6.10 Daily Average Air Temperature. Based on hourly temperatures taken at Ft. Wainwright, Fairbanks, Alaska. (Kurtz and others, 1966)

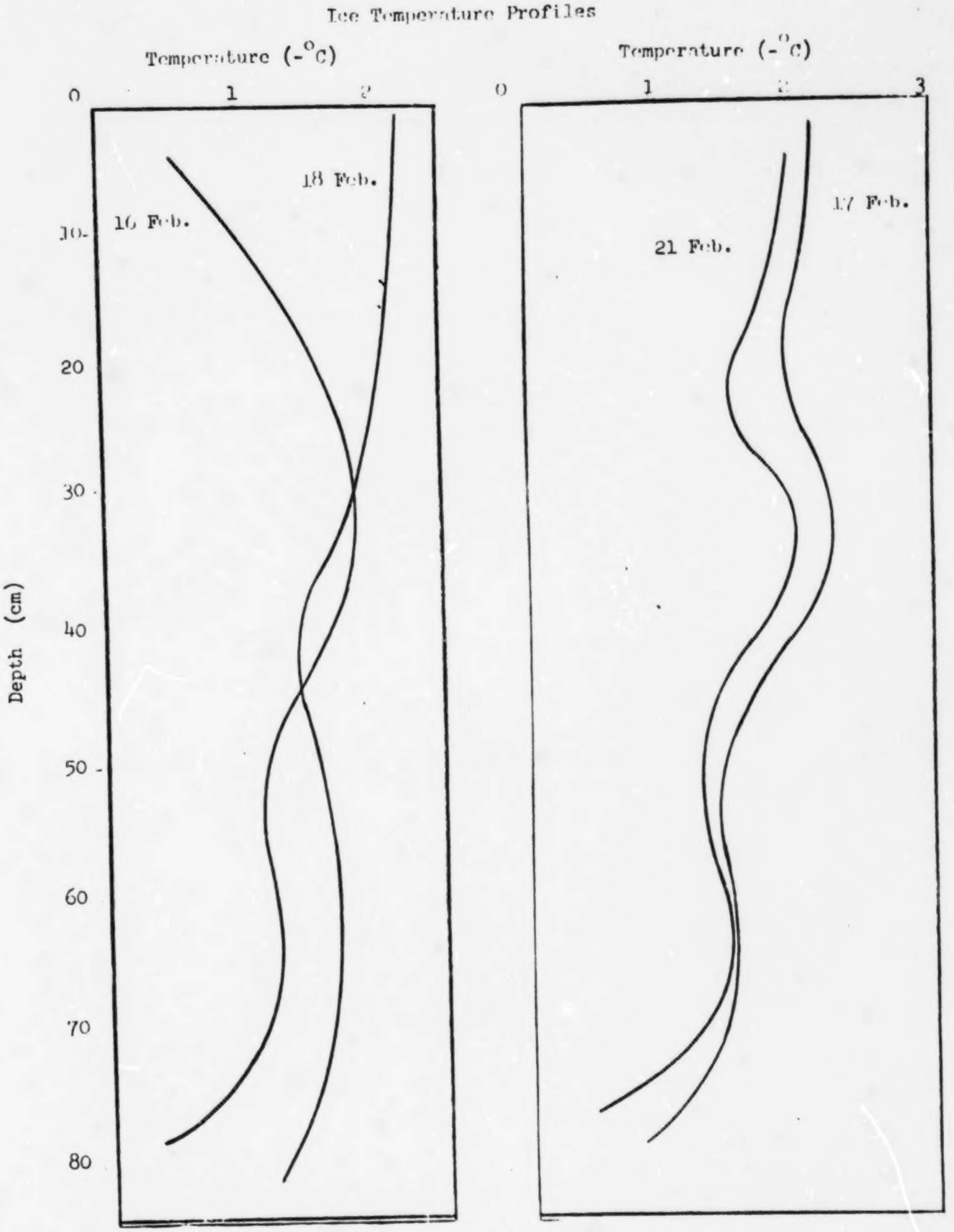


Figure 6.11 Ice Temperature Profiles. Notice the drop in ice temperature after 16 Feb. This again is caused by the drop in air temperature. (Kurtz and others, 1966)

TABLE 6.1 ICE THICKNESS AND SNOW DEPTH

Shot Number	Ice Thickness (inches)		Snow Depth (inches)
	Ground Zero Hole	Average Near Crater	
1	35	34.4	18.7[a]
2	34	33.5	19.9[a]
3	39	35.8	18.7[a]
4	30	29.8	19.8[a]
5	33	31.6	18.6
6	33	30.9	18.1
7	32	33.0	-
8	33	31.9	18.1
9	33	31.6	15.8
20	33	32.8	16.0
21	30	31.0	15.4
22	31.5	32.2	15.5
23	33	31.4	15.7
24	31	31.3	15.7
25	36	36.1	15.8
FF1	29	27.9	-
FF2	29	-	-
31	36	34.5	12.3[a]
Row A	34.7	33.3	16.6
Row B	30.5	32.4	17.0
Row C	33	33.0	12.3

[a] Cleared from ground zero area prior to detonation

(Kurtz and others, 1966)

TABLE 6.2 OBSERVED CRACK DATA

	Circumferential		Radial	
Shot Number	Number	Distance from Edge (ft)	Number	Maximum Distance from Edge (ft)
1			1	30
2	1	8.1		
3	1	32		
4	1	75		
5	2	68/80		
6			1	102
7				
8			3	39/104/204
9	1	13		
20				
21	3	55/115/200		
22	3	24/46/82		
23	1	47		
24	2	30/42		
25	3	43/62/86		
FF1	1	70		
31	1	104		
Row A				
Row B	2	17/27		
Row C				

(Kurtz and others, 1966)

TABLE 6.3 REFREEZE DATA

Date Measured	Ice Thickness (in.)							
	Shot 1 17 Feb	Shot 2 17 Feb	Shot 3 18 Feb	Shot 4 18 Feb	Shot 5 19 Feb	Shot 6 19 Feb	Shot 7 20 Feb	Shot 8 20 Feb
19 Feb	7.7	4.0	4.1	8.2				
20 Feb					7.6	6.5		
21 Feb	8.5	5.1	8.2	6.3	7.5	-	2.2	4.2
23 Feb	12.0	9.6	13.2	12.4	17.0	19.0	7.0	14.5
25 Feb	14.0	11.5	14.2	13.5	17.8	19.8	9.4	17.3
28 Feb	16.5	13.6	17.7	15.1	19.2	21.2	12.5	20.0

(Kurtz and others, 1966)

"The data show that the shallow-placed shots yield a hole relatively free of slush. This is important as a hole clear of slush will refreeze at a slower rate than one with slush present.... The bearing capacity of the two types of refrozen holes will be approximately the same for identical ice thickness....

"In general, it is concluded that:

1. The relationship between depth of detonation and ice crater radius has been defined for 136 pound C4 spherical charges in fresh water varying in depth from 10 to 52 feet and covered with three feet of ice. (Figure 1.5)

2. The reflection of the shock wave from the lake bottom for the BREAKUP experiments did not appear to enhance the crater dimensions for the 136-pound shots.

3. The row charge crater dimensions were defined for 136-pound charges spaced at 1.0, 1.5, and 2.0 times the maximum obtainable single charge crater radius. (Figure 1.5)

4. Cracks appeared to propagate better from larger yield explosions under ice of the same thickness.

5. There does not appear to be any evidence of bubble coalescence in row charge detonations in water under ice.

6. Commonly used scaling laws may be used for estimating the effects of higher yield ice cratering explosions. (Figure 1.6)

7. The explosive charge and firing procedures used are adaptable for civil applications - such as demolition of ice jams during domestic emergency operations....

8. Maintenance of open water gaps created by ice cratering explosions in still water in the arctic is limited to a few hours because rapid refreezing occurs; however, in a stream or river, the broken ice may be moved downstream by the current, thus facilitating the maintenance of a clear channel if the craters are formed at the downstream edge of an ice sheet.

"Application of results

"General. The data obtained from the experiments may be used to:

1. Define the problem of producing linear gaps and open water channels in ice sheets by means of explosives.

2. Provide guidance for large-scale civil application of explosion-produced ice gap techniques.

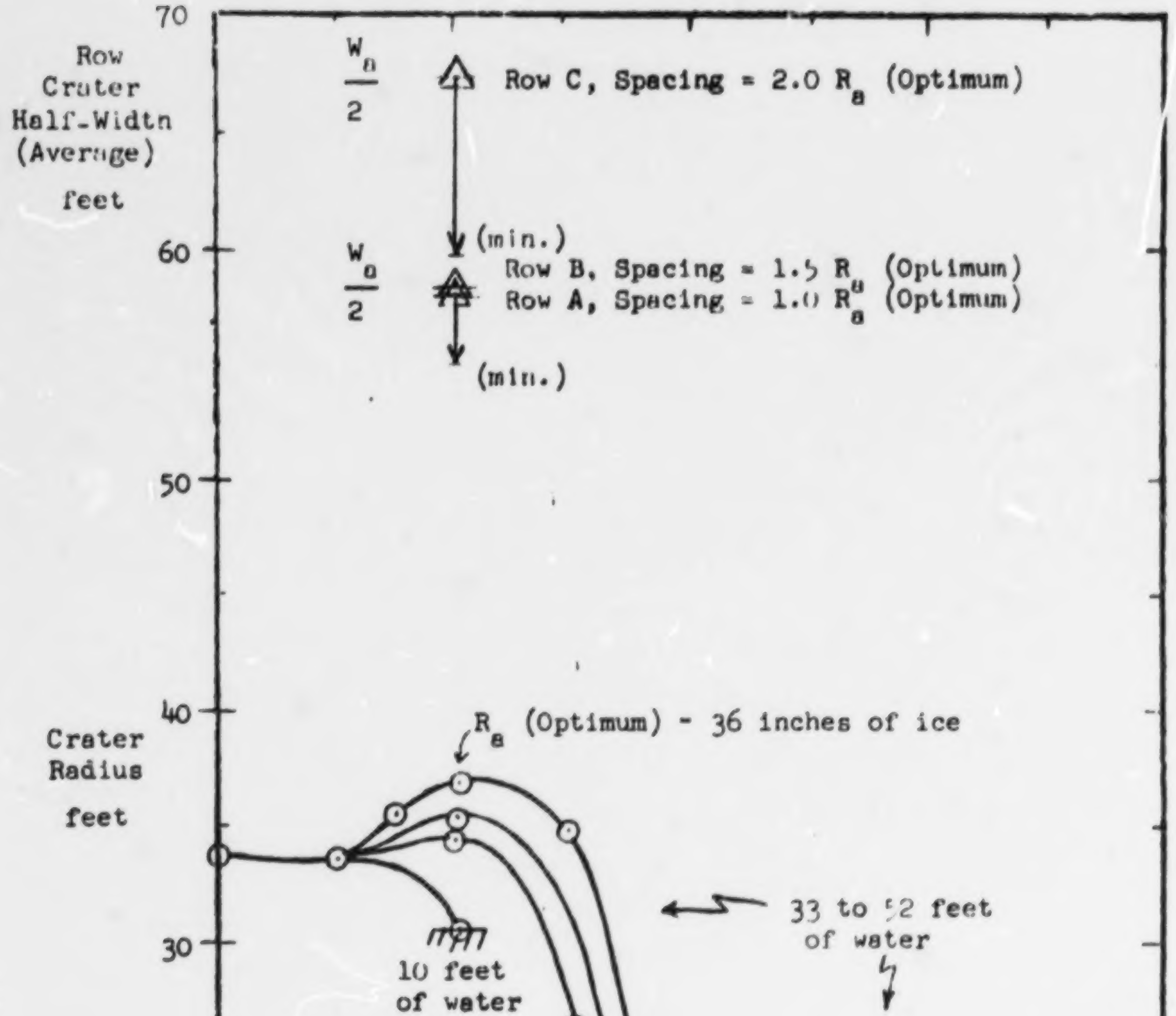
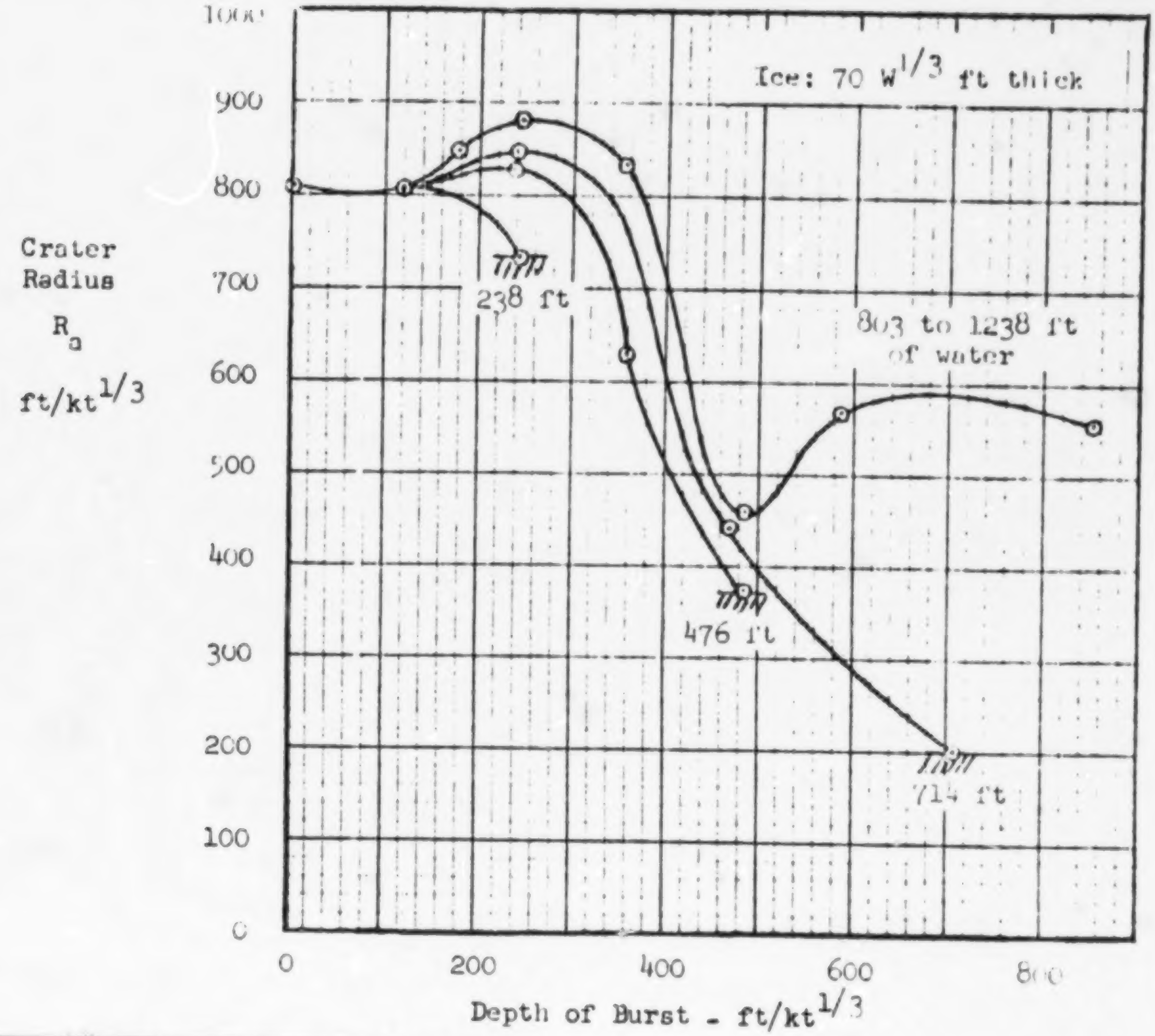


Figure 1.5 Cratering Results, 136 lb C4 Charges.

(Kurtz and others, 1966)



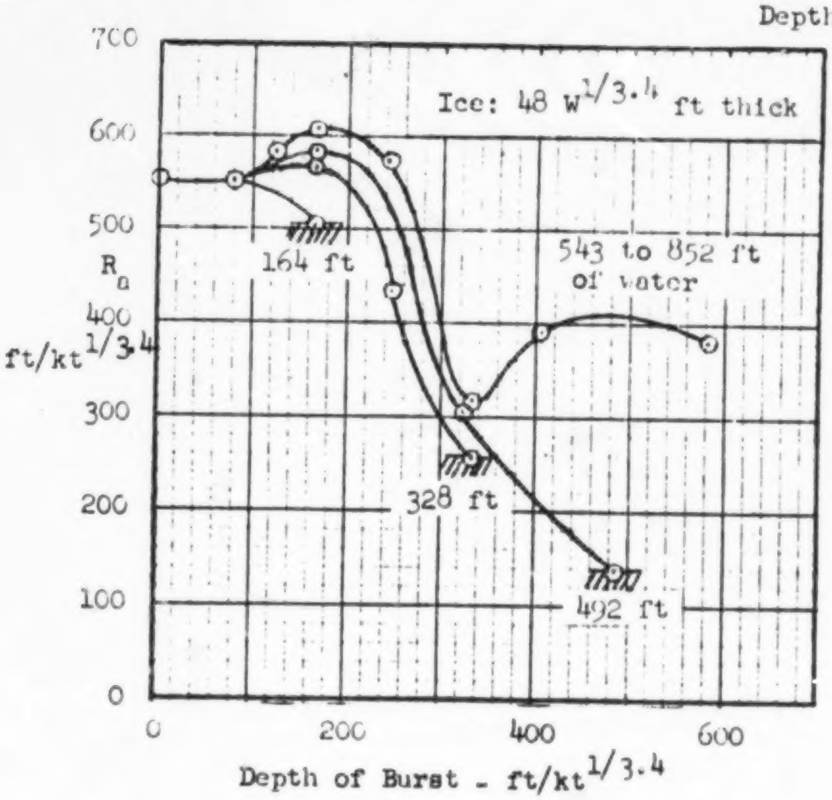


Figure 1.6 BREAKUP Cratering Results Normalized to 1 kt Energy Equivalent Yield.

(Kurtz and others, 1966)

3. Support studies by various Districts of the Corps of Engineers on the use of ice cratering in connection with emergency operations.

4. Support the development of explosion-produced ice-gap techniques.

5. Support theoretical studies of cratering physics.

"Determination of Crater Radius for Various Ice Thicknesses. Figure 1.7 is a graph which can be used to determine the required charge weight (W pounds of C4) explosive to create a hole of maximum radius (R_a feet) in ice of various thicknesses (t feet) when emplaced at the optimum depth of burst (DOB feet) below the ice. Figure 1.7 is based on the BREAKUP deep water results in 36 inches of ice and other experiments in other thicknesses of ice....

"For situations where a different charge weight must be used (because or pre-fabricated weights or need to create a hole of given dimensions) Figure 1.7 may be used to formulate a model. Corrections are then applied to the model to account for the distortions created by use of other than optimum charge weight. The adjusted crater radius desired (R_{adj} feet) and the adjusted yield (Y pounds of C4) are determined from the following relationships based on shot 31 and other experiments with varying charge weights

$$Y = W \left(\frac{R_{adj}}{R_a}\right)^{2.4} \text{ or } R_{adj} = R_a \left(\frac{Y}{W}\right)^{1/2.4} \qquad (1.1)$$

where the adjusted DOB = 1.98 $Y^{1/3}$ and where R_a and W are determined from Figure 1.7 for the given ice thickness t.

"The following examples illustrate the use of Figure 1.7 and the foregoing equations:

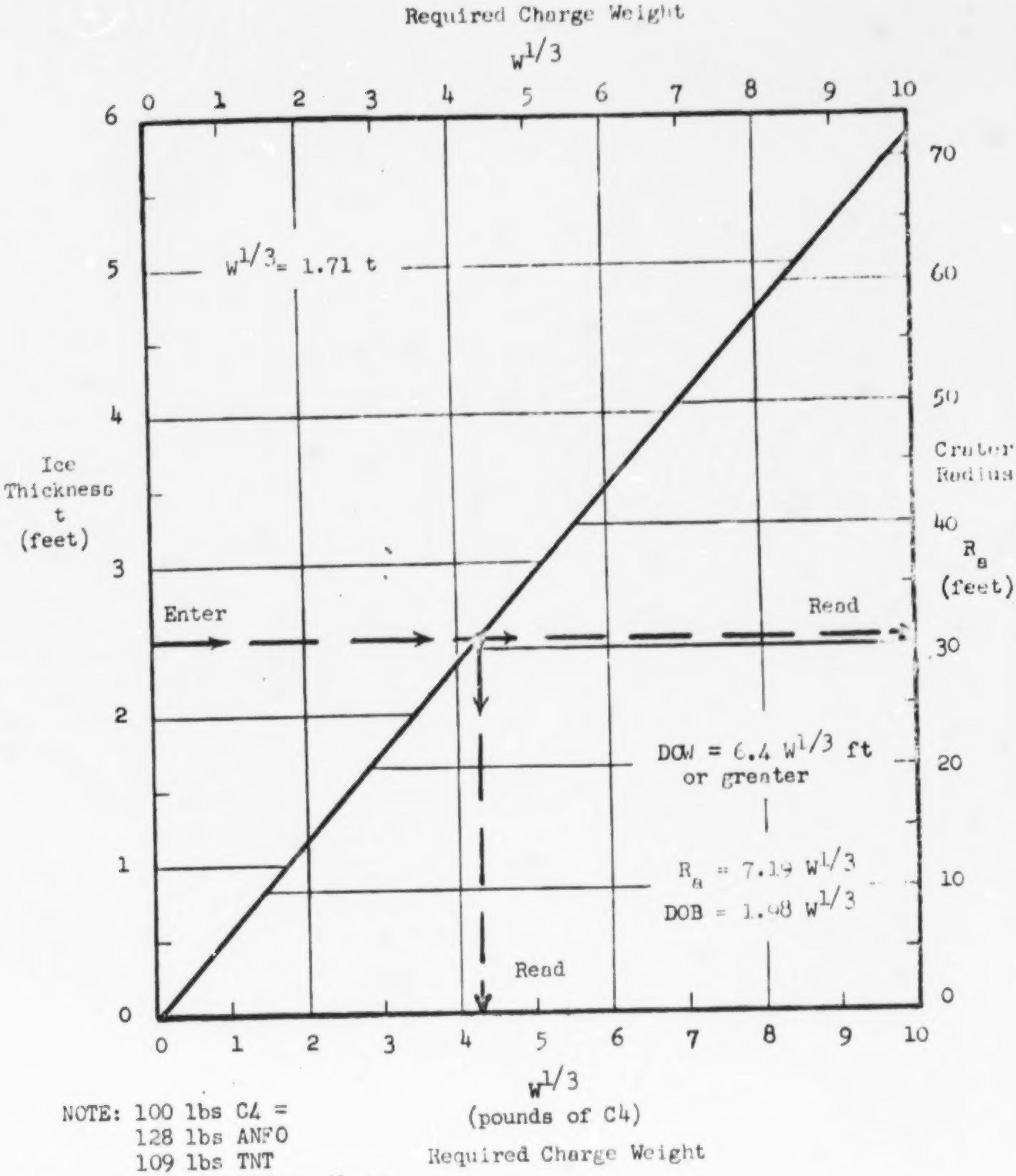
"Problem: Given 30 inches of ice, what charge weight and emplacement will give optimum crater radius in deep water?

Solution:

Step 1: Enter Figure 1.7 with 2.5 ft of ice and read $W^{1/3} = 4.3$ and $R_a = 30.5$ ft.

Step 2: Calculate $W = (4.3)^3 = 80$ lbs C4

Step 3: Calculate $DOB = 1.98 (W)^{1/3} = 1.98 (4.3) = 8.5$ ft



NOTE: 100 lbs C4 =
128 lbs ANFO
109 lbs TNT
102 lbs Nitromethane

Figure 1.7 Ice Thickness *vs*. Required Charge Weight; Required Charge Weight *vs*. Crater Radius.

(Kurtz and others, 1966)

"Continuing Problem: If a pre-fabricated charge of 120 pounds of TNT were used, what would be the resulting crater radius and the new depth of burst?

Solution:

Step 4: Convert to C4 equivalent: From Note on Figure 1.7, 109 lbs TNT = 100 lbs C4. Therefore, C4 equivalent = $\frac{100}{109}$ (120) = 110 lbs C4 or Y = 110 lbs

Step 5: Using equation 1.1 calculate the adjusted crater radius: $R_{adj} = R_a \left(\frac{Y}{W} \right)^{1/2.4} = 30.5 \left(\frac{110}{80} \right)^{1/2.4} =$ 34.8 ft

Step 6: Calculate the adjusted DOB:

$DOB_{adj} = 1.98Y^{1/3} = 1.98 (110)^{1/3} = 9.5$ ft

"Continuing Problem: If the water is 20 feet deep, how will this affect the crater radius for a 110 pound charge?

Solution:

Step 7: Calculate the scaled depth of water for W = 136 lbs and determine if an adjustment is needed:

$DOW_{136} = DOW_{110} \left(\frac{W}{Y} \right)^{1/3} = 20 \left(\frac{136}{110} \right)^{1/3} = 21.5$ ft

This value of 21.5 feet is less than 33 feet upon which the deep water curve, Figure 1.5, is based. Therefore, an adjustment is needed. (No correction is needed for depths greater than 33 feet.)

Step 8: Enter Figure 1.5 to determine for DOW = 21.5 ft, that R_a is 34.5 feet versus 36.9 feet for 136 lbs in deep water.

Step 9: Revise R_{adj} from Step 5 using the proportions obtained in Step 8:

$R_{adj} (20) = 34.8 \left(\frac{34.5}{36.9} \right) = 32.5$ ft (A lesser radius results.)

"Practical Applications. Figures 1.5 and 1.7 may be used to estimate the cratering effects of high explosive charges in various civil applications to break and clear ice.... The following describes additional considerations for specific applications.

"Prevention of Ice Jams. To prevent an ice jam, first identify the area on a river where jams occur regularly and determine the expected ice thickness. Use Figures 1.5 and 1.7 to estimate the desired charge weight for the water depths expected. Pre-fabricate and stockpile charges. Emplace the charge; stem the hole with ice and detonate the charge after the ice is formed but while there is still a current elsewhere to carry the broken ice away. Work from the downstream end, using simultaneous detonations where possible. If row charges are used, space at 4 R_a optimum for initial trials and subsequently change the spacing to that at which the current will still displace the cracked ice and large floating blocks. By displacing the ice early the probability of an ice jam is reduced considerably.

"Demolition of Ice Jams. Estimate the equivalent ice thickness and use Figure 1.7 to determine a charge weight. Assemble the charges. Depending on charge weights and depth of burst possible, use Figure 1.5 and Equation 1.1 to adjust the expected R_a for depths of burst in or under the ice. Emplace the charges and stem the emplacement holes with ice. Space charges at 2 R_a for the initial detonation and subsequently adjust the spacing until adequate cracking is obtained to allow the current to displace the cracked ice. This charge spacing, if oriented in a direction nearly parallel to the current, may also create a channel through which water may flow, thus assisting breakup."

In an unofficial memorandum pertaining principally to the engineering properties and crater hole measurements at Blair Lake, Frankenstein and Smith (1966) reports on some field usage of the tests.

"The results of the Blair Lake tests were used on explosive placement on the Mississippi River near Elk River, Minnesota. The purpose of the Minnesota tests was for the elimination of ice jams. Where possible the crater hole diameter was measured. These measurements, along with the Blair Lake measurements, were plotted according to the cube root of the charge weight versus crater hole diameter. The results of this plot are shown in Figure 8. The crater information for the Minnesota tests are also listed in Table III. The ice of the Mississippi River was partially deteriorated and much weaker than the ice of Blair Lake. There was slush under the Mississippi River ice but since slush has little or no shear strength it had no effect on the test results.

"... In Figure 8 the upper two points are from the results of the Blair Lake tests and the two lower points from the Mississippi River tests. The Blair Lake ice was thicker and stronger than the thin, weaker ice of the Mississippi River. The resulting curve of Figure 8, being a straight line, indicates that the ice thickness and strength may not have the effect on crater size as one would imagine...."

TABLE III

Individual Charge Information

Charge Number(1)	Charge Weight (lbs)	Water Depth(2) (ft)	Placement(3) Position (ft)	Crater Hole Diameter (ft)	Ice Thickness (in.)	Snow Depth (in.)
1	136.5	41.0	0	67.8	34.4	18.7
2	135	46.8	5	67.2	33.5	19.9
3	130	37.0	10	72.7	35.8	18.7
4	141.5	38.4	15	70.5	29.8	19.8
5	130	49.2	20	38.0	31.6	18.6
6	142	51.5	25	48.4	30.9	18.1
7	138	45.0	7.5	71.4	33.0	-
8	127.5	54.4	35	45.5	31.9	18.1
9	130.5	12.8	10	60.4	31.6	15.8
20	140	23.8	10	70.0	32.8	16.0
21	134.5	22.6	15	52.7	31.0	15.4
22	130.5	22.2	19.5	30.9	32.2	15.5
23	135	32.6	10	70.8	31.4	15.7
24	142.5	31.6	20	37.6	31.3	15.7
25	140.5	33.0	30	17.0	36.1	15.8
31	940	52.0	19	167.2	34.5	12.3
FF-1	160	53.8	35	47.4	27.9	-
M-1	50	14	11	42.4	19.5	0
-2	50	13	10.5	40.1	19.5	0
-3	33.3	11	1.0	32.0	18.0	0

(1) Shots 10-19 and 26-30 are Row shots.
M Shots are Mississippi River shots.

(2) Water depth is to top of ice.

(3) Placement position is from bottom of ice to center of charge.

(Kurtz and others, 1966)

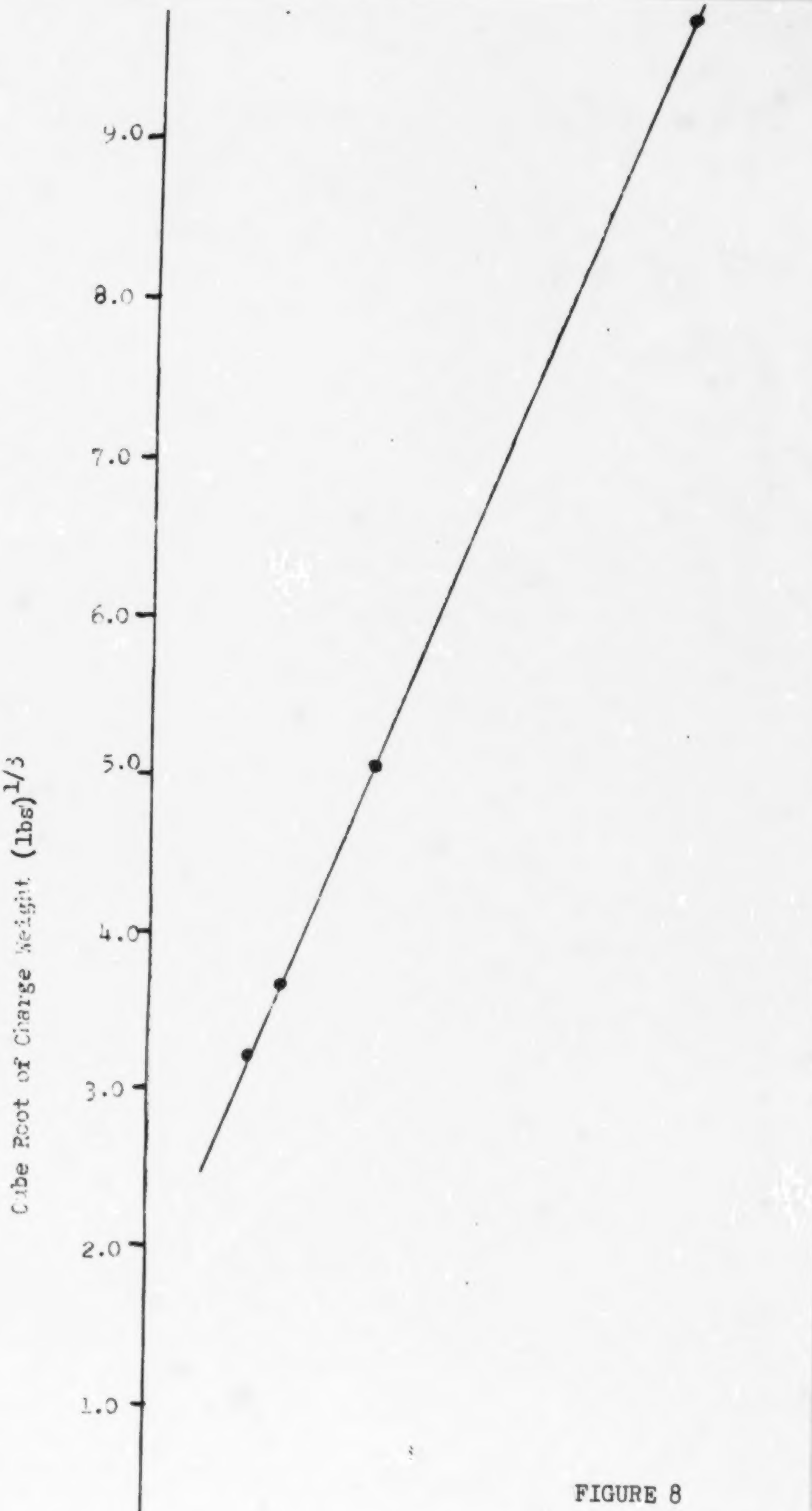


FIGURE 8

(Frankenstein and Smith, 1966)

Purple (1965) describes some crater hole measurements on Korean river ice.

> "Experiments with C-4 explosive were made to determine the most effective method of breaking up the ice. Charges of 5 pounds of C-4 were placed at depths of 10 feet, 5 feet, 2 feet, just below the 4- to 6- inch ice sheet, and on top of the surface with the following results:

RESULTS

Depth of Charge	Size of Hole	Size of Ice Fragments
10 feet	10 feet	2 feet
5 feet	16 feet	1½ feet
2 feet	22 feet	1 foot
Just below ice	30 feet	1 foot
On top of ice (tamped with sand bags)	24 feet	1½ feet

C-3 & Tetrytol

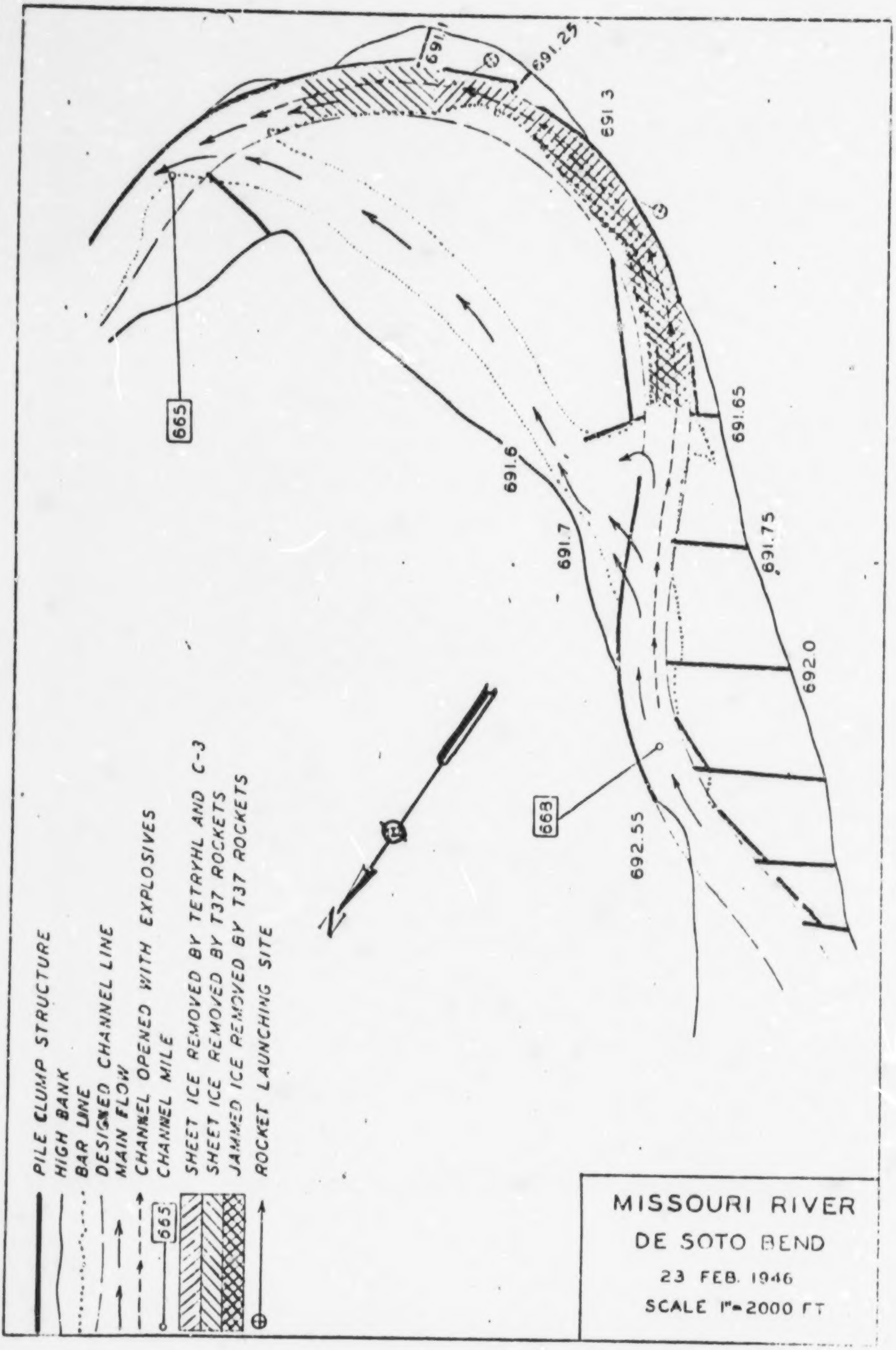
Composition C-3 is principally used as a main charge or booster for cutting and breaching. A special blasting cap is required for detonation. Its relative effectiveness as an external charge and velocity of detonation are equivalent to C-4. Its value as a cratering charge is excellent and water resistance is good. The intensity of poisonous fumes, however, is dangerous.

The principal uses and detonation requirements of tetrytol are similar to C-3. Relative effectiveness as an external charge is 1.20 and velocity of detonation is 23,000 fps. Its value as a cratering charge is fair and water resistance is excellent. Poisonous fumes are dangerous (Department of the Army, 1962). Tetrytol pellets are also used as booster charges for C-4 (Kurtz, Benter, Christopher, Frankenstein, Van Wyhe, and Rogusi, 1966).

Composition C-3 is less sensitive than tetrytol, and from -20F to 125F, it is plastic and can be molded into any shape desired (Moran, 1946).

Moran (1946) ran tests on C-3 and tetrytol on ice jams near Corning, Missouri; Blair, Nebraska; Onawa, Iowa; and Decatur, Nebraska.

> "... Tests ... demonstrated that the maximum propagation distance for a 20-pound charge of Tetrytol is 24 inches, and the corresponding distance for an 18-pound bag of C-3 is 18 inches. It was also found that a No. 6 commercial blasting cap will not detonate C-3 unless detonation cord is added as a booster....
>
> "The two explosives were tested concurrently throughout the project in charges of various sizes. Where reliability of detonation was paramount, Tetrytol was used or C-3 charges were primed with a block of Tetrytol. There was no appreciable difference in the results obtained from the two explosives....
>
> "A 2,000-foot section of sheet ice, approximately 500 feet in width and from six to eight inches in thickness, was successfully broken up by use of Tetrytol and Composition C-3 in DeSoto Bend on 23 February (See Figure 3). There was a good current flowing beneath the ice and a clear channel downstream. The ice was beginning to rot and was apparently unsafe to walk out upon. The condition of the ice limited the placement of the charges to hand casting from the bank, which in turn restricted the size of the charges.... In all, one 10-pound charge and 13 charges of 4½ to 6-3/4 pounds each, were cast upon the ice from 50 to 100 feet from the bank at from 1- to 5-minute intervals. Some of the explosions opened small cracks radiating crosswise of the channel from the hole,


PILE CLUMP STRUCTURE
HIGH BANK
BAR LINE
DESIGNED CHANNEL LINE
MAIN FLOW
CHANNEL OPENED WITH EXPLOSIVES
665
CHANNEL MILE
SHEET ICE REMOVED BY TETRYHL AND C-3
SHEET ICE REMOVED BY T37 ROCKETS
JAMMED ICE REMOVED BY T37 ROCKETS
ROCKET LAUNCHING SITE
MISSOURI RIVER
DE SOTO BEND
23 FEB. 1946
SCALE 1"=2000 FT
N
665
663
691.1
691.25
691.3
691.6
691.65
691.7
691.75
692.0
692.55

(Moran, 1946) FIGURE 3

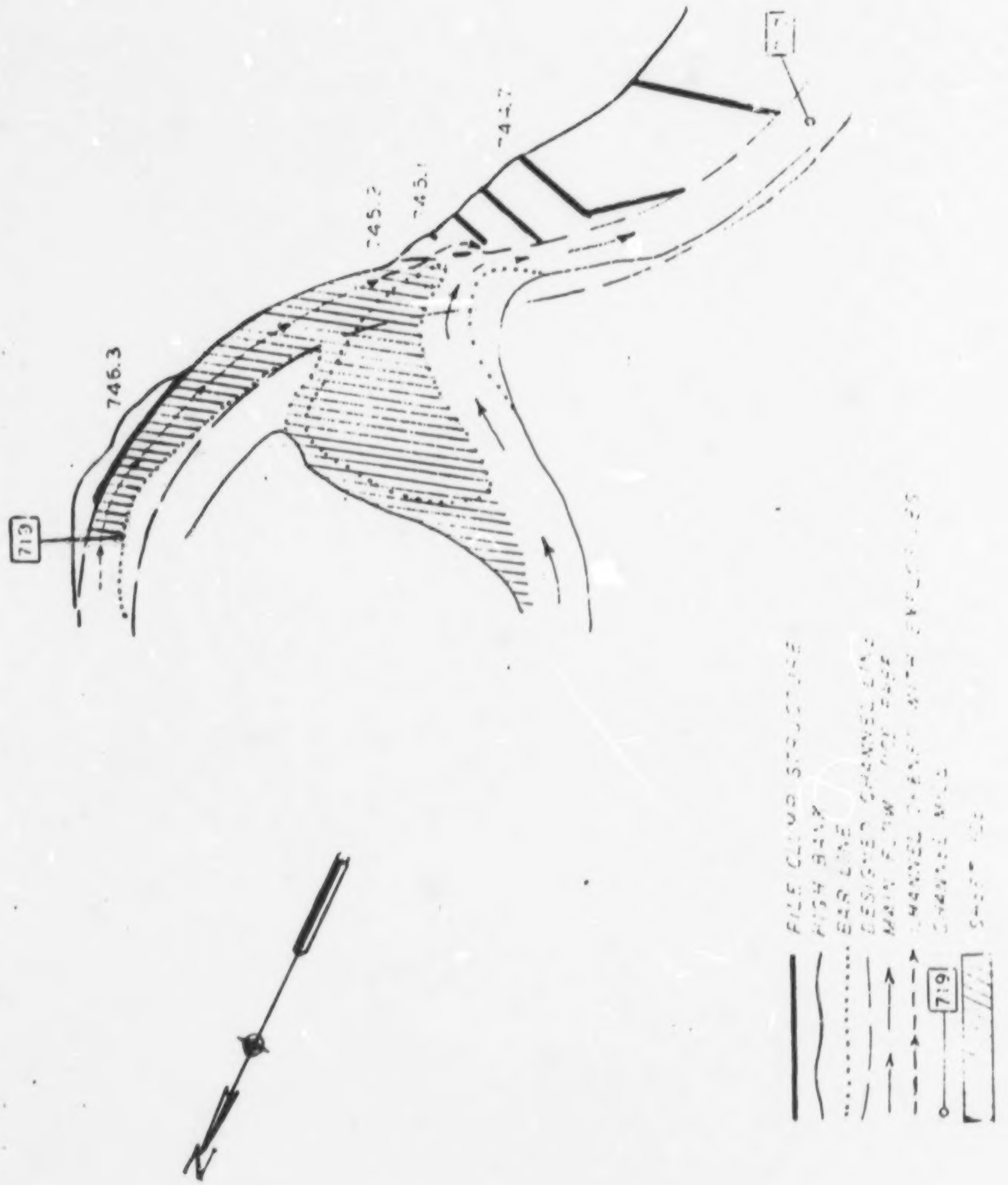
and following each explosion, whether accompanied by cracking or not, a concussion wave could be seen to radiate from the hole. Usually following a series of from two to four explosions, a crack would open up clear across the channel at a distance of from 100 to 300 feet upstream from the holes made by the last explosion, and a large section of ice would break away. In one instance a 350-foot section of ice 500 feet wide broke away following the explosion of a 4½-pound charge.

"The clearing of the 2,000-foot length of channel by means of the small hand-cast charges, was accomplished in 68 minutes. The next 1,500 feet of similar ice was removed by the use of four rockets in 15 minutes (see Aerial Explosives). Seven 6¼-pound charges were then used on the heavier ice at the foot of the jam, but they were too small to have any appreciable effect.

"Composition C-3, primed with Tetrytol, was used to break up heavy sheet ice which was hanging in a dike system in Tieville Bend near Onawa, Iowa, on 27 and 28 February 1946. This operation was extraordinary in that the ice being cleared was not in the main channel and would not ordinarily require removal. However, in this instance a sand bar projecting downstream from an island to near the river end of a dike, precluded the opening of the main channel around the river end of the dike and necessitated the clearing of a temporary channel through gaps in the dike system for passage of upstream ice which was proposed to be blasted from the main channel. To accomplish this a way had to be cleared through a 250-foot gap in dike No. 745.2, and through an approximately 125-foot gap in dike No. 745.1 (See Figure 4). The operation was handicapped by: a strong eddy action caused by the main flow which was reentering the channel opposite the point of operation; the presence of the bar and shallow water along the right flank and approximately 360 feet of pile-clump dike structure along the left flank of the ice above the dike system; and by a very slow flow through the main channel under the ice. The ice hinged on the dike structures at both ends of the two gaps and had to be broken off in small pieces, even after the ice at the hinges had been cleared away.

"Twelve small charges of Tetrytol, consisting of one 10-pound charge, six 5-pound charges, and five 2½-pound charges, were cast by hand from the bank along the upstream side of the shore section of dike No. 745.1. The explosions loosened the ice along the shore portion of the dike line, but the charges could not be thrown far enough to reach the end of the dike, and the ice thus loosened, except for small pieces, could not pass through the structure. It became necessary to use a skiff from which to place the charges, and by this means ten 20-pound charges, placed two or three at a trip, were successful in clearing the gap in dike No. 745.1 and the outer hinge of ice spanning the gap in dike No. 745.2.

"The next day, 28 February, twenty-five 18½-pound charges were required to clear the gap in dike 745.2, and the way was now open to blast the ice which was sandwiched between the shallow bar and the approximately 360-foot


746.3
745.2
745.1
713
N
PILE CLUMP STRUCTURE
HIGH BANK
BAR LINE
DESIGNED CHANNEL LINE
CHANNEL MILE
7:9

MISSOURI RIVER
TIEVILLE BEND
26 & 27 FEB. 1946
SCALE: 1"= 2000 FT.

394 (Moran, 1946) FIGURE 4

shore section of dike No. 745.2. Ten 18½-pound charges were placed in series, spaced 20-25 feet apart on a line approximately 15 feet upstream from the dike line. They were fired by detonating cord and exploded simultaneously, but the ice, although broken up, did not move out. Four more 18½-pound charges were exploded to thoroughly loosen the ice at the end of the dike, and eight 18½-pound charges were used to enlarge the opening at the opposite side of the gap to permit the inflow of more water from the main flow. This being done, three 18½-pound charges along the dike line and two 18½-pound charges near the shore end of the dike line started the ice, which had been previously loosened, moving out, and the dike system was clear.

"The clearing of this dike system and opening of a channel through the dikes was begun with rockets....

"The next phase of the operation involved the clearing of 1.14 miles of sheet ice from the main channel. The channel was shallow with a narrow thalweg of from four to seven feet of water. The flow was very slow, and when the ice was broken up it was necessary to push into the loosened area with the outboard motor skiff and start the broken ice downstream by propeller wash. As the operation proceeded upstream, it became necessary to cast seven 2½-pound and three 5-pound charges to keep the ice from jamming again at the head of the dike system. When these small charges appeared to be losing ground, a single 36-pound charge relieved the situation, and no more trouble was experienced at the dike system.

"Eleven 2½-pound charges and four 5-pound charges were cast from the bank before it was found that it was necessary to place charges farther from the bank than could be reached by hand casting. Then six 2½-pound, two 5-pound, and nine 10-pound charges, placed from the motorboat, succeeded in clearing approximately 2,000 feet of channel.

"The next morning ... a single 2½-pound charge, intended as a warning shot only, moved out a 300-foot section of ice, whereas a suceeding 10-pound charge produced comparatively no ice movement. Altogether, one 2½-pound charge, three 5-pound charges, and thirty-two 10-pound charges, cleared the ice from approximately 3,000 feet of channel. All charges were cast from the bank and into holes in the ice wherever possible. The current was still very slow and the motorboat was required to start the broken ice downstream. This operation required three hours and four minutes.

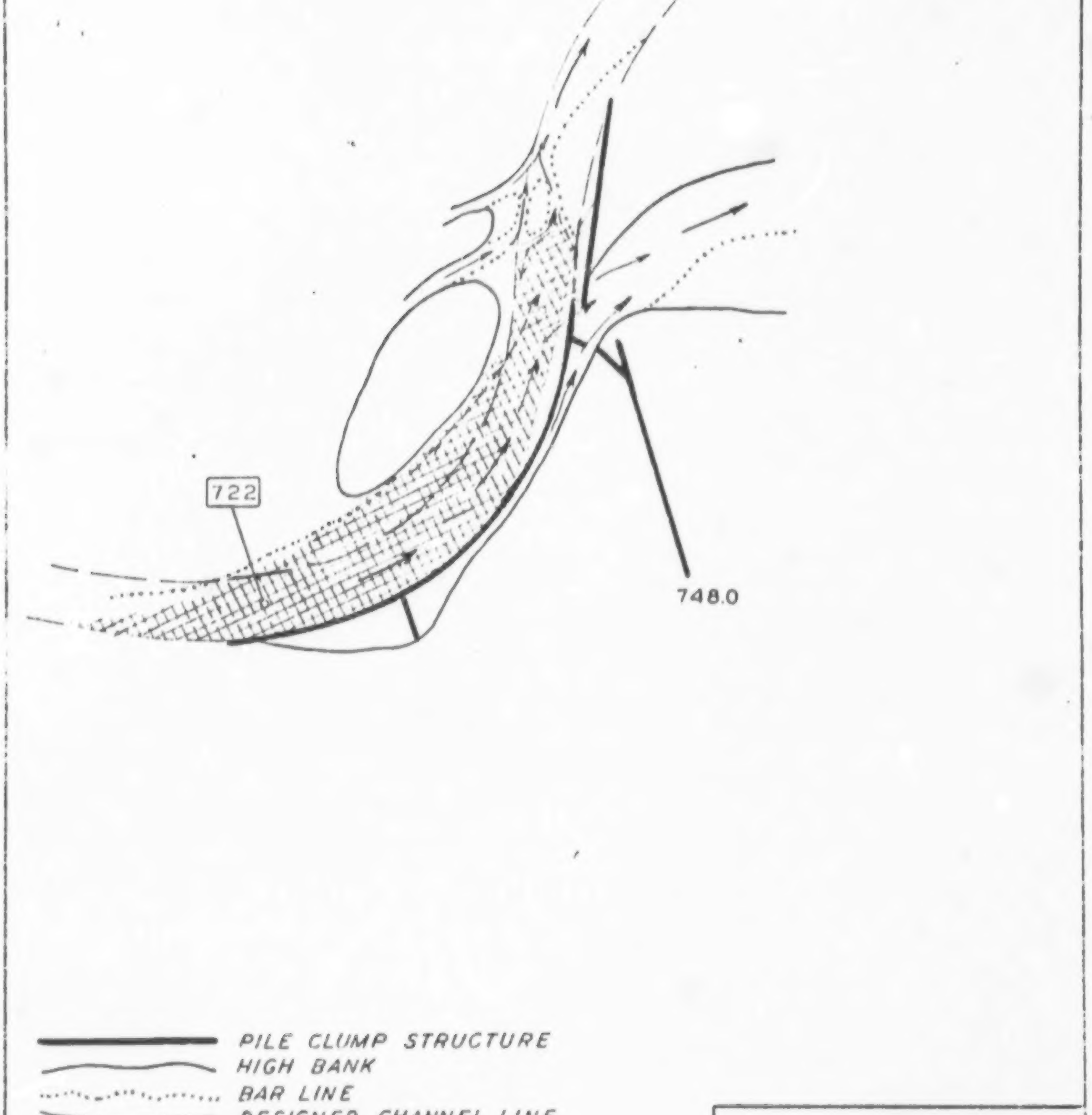
"A heavy ice jam in Black Bird Bend was attacked with Tetrytol and Composition C-3.... The jam was from 800 to 1,000 feet wide and approximately one mile long; it was composed of ice varying from 10 inches to 34 inches in thickness which, through the heaviest portion was piled five to six feet above the water surface. The jam was caused by an extensive sand-bar area over which the ice could not flow at the river stage then existing. There was a good flow of water under the ice, but it was flowing through a dyke and escaping through a deep right-bank chute which headed a short distance above the sand-bar area. There was very little or no flow of water through the sand-bar area. The dike, a longitudinal pile-clump structure crossing the head of a chute, was protected from the jam by a shelf of sheet ice from 100 to 200 feet in width. The only water below the jam was that which was flowing from a small left-bank chute which entered the main channel at a point near the downstream end of the sand-bar area (See Figure 5).

"Inasmuch as the sheet ice along the dike structure was apparently protecting the structure from damage by the jam, it was decided to not disturb the sheet ice but instead to open a channel along the opposite side (left bank) of the river, if possible....

"All efforts to locate a ... suitable channel through the bar area were futile, and the plan was revised to the simple loosening of the ice along the left bank, so that if a rise in river stage should occur the loosened ice would be washed over the bar. A total of three 5-pound charges, seventy-one 10-pound charges, and seven 18-pound charges, were cast along the bank over a distance of approximately 1,500 feet. The explosives loosened the ice, but there was no appreciable movement in the jam.

"During the night a flash rise of approximately two feet evidently carried the loosened ice over the bar, as there was a heavy run of ice of six hours' duration passing ... about two and a half miles downstream. The next morning it was found that the downstream 300 feet of the 1,500 feet which had been loosened during the previous afternoon, was open. It appeared that most of the ice which had been loosened had moved over the bar, but it had been replaced during the night by additional ice which had moved down from the upper end of the jam. The jam now had a length of one and a half miles....

"The party continued the plan of loosening the ice along the left bank in hope of another rise in stage to carry the ice over the bar. Where possible the charges were cast into holes between the ice cakes. One 37-pound charge and forty-nine 18½-pound charges were placed in this manner; one 74-pound charge and two 37-pound charges were hand placed out on the ice, and in one instance fifteen 18½-pound charges were carefully lowered in cracks between ice cakes and exploded simultaneously with detonating cord. The day's work opened a clear channel approximately one-half mile long. It pierced the heaviest portion of the jam and released a small head of water. As the ice was broken up by the explosions, it moved down swiftly but milled around and finally packed at the lower end of the jam, while the water in the channel thus opened crossed the river, passed under the sheet of ice and through the dike into the chute. Inasmuch as there was insufficient water to pass the ice over the bar, the experiment was terminated."


N
720
722
748.0
PILE CLUMP STRUCTURE
HIGH BANK
BAR LINE
DESIGNED CHANNEL LINE
MAIN FLOW
CHANNEL OPENED WITH EXPLOSIVES
720 CHANNEL MILE
JAMMED ICE
SHEET ICE

MISSOURI RIVER
BLACK BIRD BEND
1 & 2 MARCH 1946
SCALE 1"=2000 FT.

(Moran, 1946) FIGURE 5

"Discussion of operations on ice

"Conditions in DeSoto Bend on 23 February were ... favorable for blasting operations, as there was still a good current flowing under the ice when the blasting operation began (See Figure 3). Small charges of Tetrytol and Composition C-3, from 4½ to 10 pounds, cast by hand from the bank, were successful in removing sheet ice but had very little effect on the jammed ice. It appears probable that even better results could have been obtained with Tetrytol and C-3 if larger charges could have been placed farther from the shore, but this was not possible as there was no means available by which men could safely proceed out upon the ice....

"It was found during the experiment in DeSoto Bend that no immediate result can be expected to follow the explosion of any one charge, but each explosion created a consussion wave under the ice which extended 200 feet or more upstream.... These recurring waves, resulting from a series of three or more charges, developed a break, not at the spot of the explosion but at some distance upstream."

"Removal of the ice from the dike system and designed channel in Tieville Bend was prerequisite to the later operation in Black Bird Bend, a few miles upstream. The ice in Tieville Bend was not properly an ice jam and did not have either the clear outlet or sufficient water that is ordinarily required to successfully blast an ice jam.... Some of the charges had to be placed where the water was known to be shallow, because the ice over the deeper water could not be reached....

"It was definitely observed during the operation that underwater charges were much more effective than similar charges placed on the surface of the ice. The underwater charges created a better upheaval, a stronger concussion wave under the ice, did not throw ice particles far from the explosion, and the sound effect was not so disconcerting.... Consequently, the charges were thrown through holes in the ice wherever possible, but the actual comparative effect of surface and underwater charges was not determined.

"The ice jam in Black Bird Bend had a good current of water beneath it and a small head of water behind it, but the only possible outlet for the jam was blocked by a sand bar.... Single 18½-pound charges had more effect than multiple smaller charges. Charges cast into holes between the cakes were more effective than charges placed on top of the ice. The best results were obtained by carefully lowering 15 sacks, approximately 278 pounds, through holes in the ice, and detonating all the charges simultaneously with detonating cord; but it was found that such an operation cannot be repeated in the same area, because the explosion of multiple charges weakens the surrounding ice to the extent that it is unsafe to walk upon. Two 37-pound charges, placed on top of the ice, approximately 50 feet apart, did not give as good results as would four 18½-pound charges spaced under water over the same distance. Nor did one 74-pound charge, placed out on the ice, approximately 150 feet from shore, have sufficient effect to warrant repeating the operation.

"However, the experiment in Black Bird Bend did demonstrate that jams composed of jammed ice cakes up to 34 inches in thickness can be broken up with 18½-pound charges of Tetrytol or Composition C-3. A channel 30 feet wide and approximately one-half mile long was cleared by use of fifty-two 18½-pound and seven 37-pound charges. It was also found that the results obtained are proportional to the care and time taken in placement of the charges.

"Finding

"During the course of the experiments it was found:

"A clear channel below the jam and a flow of water of sufficient velocity and depth to carry the loosened ice away, are prerequisite to the successful removal of an ice jam by use of explosives."

"Given a partially blocked outlet and a good flow beneath the jam, it is possible to blast a channel along one side of the jam to tap a head of water being held in or behind the jam.

"Removal of an ice jam by blasting can reduce the possibility of damage to structures, and can accomplish a savings in the cost of maintenance of structures far in excess of the actual cost of the blasting operation.

"If an ice jam is to be blasted, operations should begin as soon as possible after the formation of the jam has been reported.

"Tetrytol and Composition C-3 are both suitable for the blasting of ice from 6 inches to 34 inches in thickness. Because it is primed with detonating cord, Tetrytol is more reliable of detonation than Composition C-3, and is more convenient for use in small charges. However, Composition C-3 is slightly safer to drop; it provides a heavier explosive impact, and for more reliable detonation it can be primed with a block of Tetrytol or with a booster of detonating cord. Both explosives are much safer to handle than is dynamite."

"... Underwater charges are more effective than surface charges. Multiple charges, exploded simultaneously, are more effective than a similar number of single charges. However, no large operation can depend upon the placement of multiple charges alone, and single charges will be required."

TNT

TNT is basically used as a main or booster charge for cutting and breaching. A special blasting cap is required. Its relative effectiveness as an external charge is 1.00. Velocity of detonation is 21,000 fps. Value as a cratering charge is rated as good, but intensity of poisonous fumes is dangerous. Water resistance is excellent (Department of the Army, 1962).

Thalimer and Burfoot (1960) report successful removal of an ice jam using TNT in southwestern New York State.

"The general plan for the removal of the ice jams on French Creek was to break sections from the downstream end. The size of pieces would have to be small enough to float away without causing secondary ice jams or damage to bridges....

"The plan adopted consisted of cutting a line of holes normal to the stream, 30 to 50 feet on centers with the line 50 to 60 feet back from the leading edge of the ice jam. The spacing between lines varies from 80 to 120 feet depending on breakage produced by the line shots. Center spacing of 30 to 50 feet for line holes also depended on achieving satisfactory breakage. The holes for placing charges were prepared with power chain saws...." An attempt was made previously to use shaped charges and C-4 for blowing the placement holes. "This method proved unsuccessful because the fractured area around the holes was too extensive to permit placing the TNT charges safely."

"After the holes were cleaned out, TNT charges from 8 to 16 pounds were placed in each hole and connected with primacord. A #6 non-electric cap and a time fuse were connected to the primacord on the bank, and the line of holes was fired by igniting the time fuse. Under normal conditions with average temperatures prevailing and using maximum spacing of holes and lines, 16-pound charges of TNT were found most effective.

"The flat ice encountered at the downstream and upstream end of the ice jams varied from 8 and 14 inches in thickness. Effective breakage of this type of ice is difficult, because the depth of water under the sheet ice varies. In order to obtain uniform breakage, charges placed under the sheet ice were anchored by sticks extending across the hole so that the charge could be suspended about 2 feet below the bottom of the ice. This provided a uniform water cushion between the bottom of the ice and the charges and was the most satisfactory method for removal of sheet ice. The spacing of holes used for sheet ice was the minimum distance of 30 feet, and 8-pound charges were used. It was found necessary to reduce the distance between lines of holes to between 80 and 100 feet.

"The jam or pressure ice consisted of flat ice, previously broken up by temperature rise and increased stream flow, that had lodged on bars on its passage downstream. Abnormally low temperatures then solidified the ice pack and accumulated debris into a jumbled mass of reinforced ice with planes extending in all directions. The maximum height of ice above the water surface was about 5 feet and it extended below the water surface as much as 10 feet. The spacing of holes for TNT charges in pressure ice was governed somewhat by the conditions at each line of holes across the stream. Each hole was cut as deep as possible with the ice saw and extended with the chisel point of a 6-foot posthole digger far enough to place the charge at least 2 feet below the water surface.

"Operations

"A step by step procedure for the removal of the ice jam consisted of laying out the pattern of holes for blasting; cutting and cleaning out the holes; transporting the prepared charges from the assembly station, placing them, connecting them to the line primacord, and attaching the non-electric cap and time fuse; clearing the firing area of equipment and personnel; and firing the line charges. The layout and hole-cutting crew and the clean-out crew soon progressed to a point far enough from the scene of blasting that it was safe for them to continue work while the line shots were fired. The loading and firing crew worked at the downstream face of the jam and actually combined two phases of the operation. The loading crew placed charges in the prepared line holes, tamped or anchored the charges as required so that the firing crew had only to splice the line of primacord to the individual charges, attach the detonator and time fuse, and fire the leading line. The loading crew prepared two or three lines of charges in advance of the firing crew. Multiple line shots were fired on several occasions during the early part of the operation but were abandoned because of the vagaries of breakup.

"Prior to the blasting operations on the main ice jam, careful reconnaissance downstream was required to locate and remove shore ice that formed restrictions in the channel and might cause secondary ice jams. In this type of removal the shore ice was removed by use of a 'daisy chain,' a string of small charges tied together with primacord. The 'daisy chain' was usually placed and fired by a helicopter crew.

"Damages to buildings, bridges, and utilities resulting from the blasting of the ice jams was limited by reducing the size of charges to the minimum consistent with accomplishing satisfactory results. Residents in areas adjacent to the stream were advised to leave windows and doors partly open to minimize breakage of glass from blast shock waves. The reduction in size of charges where buildingswere close to the stream banks also reduced roof damage from ice propelled by the explosions. Blasting near bridges and gas lines was conducted with all possible precaution to safeguard the structures. Men were stationed at bridges with pike poles to aid passage of the ice downstream to protect the structures.

While blasting the ice in the vicinity of a high-pressure gas line, pressure in the line was reduced as much as possible and men were stationed at the stream crossing valves to shut off the flow of gas if the lines were ruptured."

"The rate of progress, shown in Table I, indicates that an average of 1,950 feet of channel was cleared daily.... The rate of use of explosives per linear foot of channel cleared amounted to 1.12 pound. An average daily use of explosives, based on a daily rate of 2,170 feet of channel cleared, was 2,430 pounds."

Operations on the same ice jam are described in another report (Pittsburgh District, Corps of Engineers, 1960).

TNT was used in Alaska as a primer for ANFO charges placed in ice jams (Froehle, 1966).

"Charges will be primed with detonating cord and boosted with a small charge of TNT or C-4."

Van der Kley (1965) in a mathematical treatment on the use of TNT for clearing ice opposes the above views.

"To sum up: Ice-breakers are always preferable to explosives, even when large ice dams have to be dealt with. The use of explosives is only justified if it has been found impossible to break an ice dam with ice-breakers or in case of emergency."

The investigation results supporting this conclusion are given below. It is the most extensive mathematical treatment on explosives found during this survey.

The program of experiments was drawn up to "examine possibility of making effective use of explosives for clearing ice included:

a. fundamental tests on Lake Ijssel to discover the effects of explosions on ice;

b. tests with explosives on ice in the main rivers under easy conditions for ice-breakers;

c. tests with explosives on ice in the main rivers under difficult conditions for ice-breakers....

"It turned out to be possible to express the effect of the explosives on the ice in formulae by using the results of the fundamental tests referred to under a. The application of those formulae and their effectiveness was then tested."

TABLE I. STATISTICS OF ICE JAM REMOVAL

Date		Progress (feet)	Explosives (pounds)	Primacord (feet)
Jan.	29	900	800	
	30	1,100	1,000	1,000
	30	1,500	900	2,500
Feb.	1	1,600	1,100	3,700
	2	1,800	2.200	8,800
	3	2,400	1,750	7,000
	4	2,800	3,500	10,000
	5	3,200	5,500	24,000
	6	2,400	3,350	3,000
	7	2,600	2,500	12,000
	8	1,200	1,500	11,000
		21,500	24,100	88,000

(Thalimer and Burfoot, 1960)

"Fundamental tests on Lake Ijssel

"Ever since 1961 whenever there has been ice of adequate thickness, experiments have been carried out to test the effect of explosives.... The charges were placed on the ice and at various depths below it. Different sizes of charge were used. The diameter of each hole blown in the ice was measured and the thickness of the ice recorded."

"Tests with explosives on ice in the main rivers

"On 5th February 1963 ... it (was) possible to carry out a series of experiments ... on the river Waal. At that time the ice was about 25 cms thick but of such a structure that one powerful ice-breaker assisted by two of medium power managed to break about 4 kilometres of river per day over its entire width of 250 metres. That gives a capacity of about 500 metres of river per effective breaking hour using three ice-breakers.

"The effect of the detonation of charges on the solid sheet of ice was similar to that produced during the tests that had already been conducted in Veluwemeer.

"The effect on the breaking capacity of the ice-breakers of the 'softening up' of the solid sheets of ice in advance was checked by arranging the charges as shown in Figure 1.

"The charges were suspended 1 metre below the upper surface of the ice in holes made by detonating charges placed on the ice. The section 'softened up' by exploding the charges underneath the ice was then broken up by the ice-breakers. Their breaking capacity did not increase noticeably, nor did the ice show any signs of becoming detached or floating away. The final experiment consisted in detonating four heavy percussion charges placed across the river at intervals of 75 metres and 75 metres away from the downstream edge of the solid sheet of ice. The main charges weighed 9 Kgs each and the percussion charges 3 Kgs.

"Although the explosions made large holes in the ice, the rest of the solid mass was apparently still so strong that it did not become detached.

"The charge formula

"If an explosive charge is detonated in water at M (detonation point) which is at a certain depth (h) below the surface (see Figure 2), a sphere of gas of a certain volume is created.... The pressure propagates itself spherically from the detonation point through the water and the force exerted by the pressure wave thus set up mainly gives rise to a change in volume. Spherical stress has been set up. The radial stress set up in a sphere of radius r is

$$\frac{pR^2}{r^2}$$

in which p is the pressure in the sphere of gas with radius R.

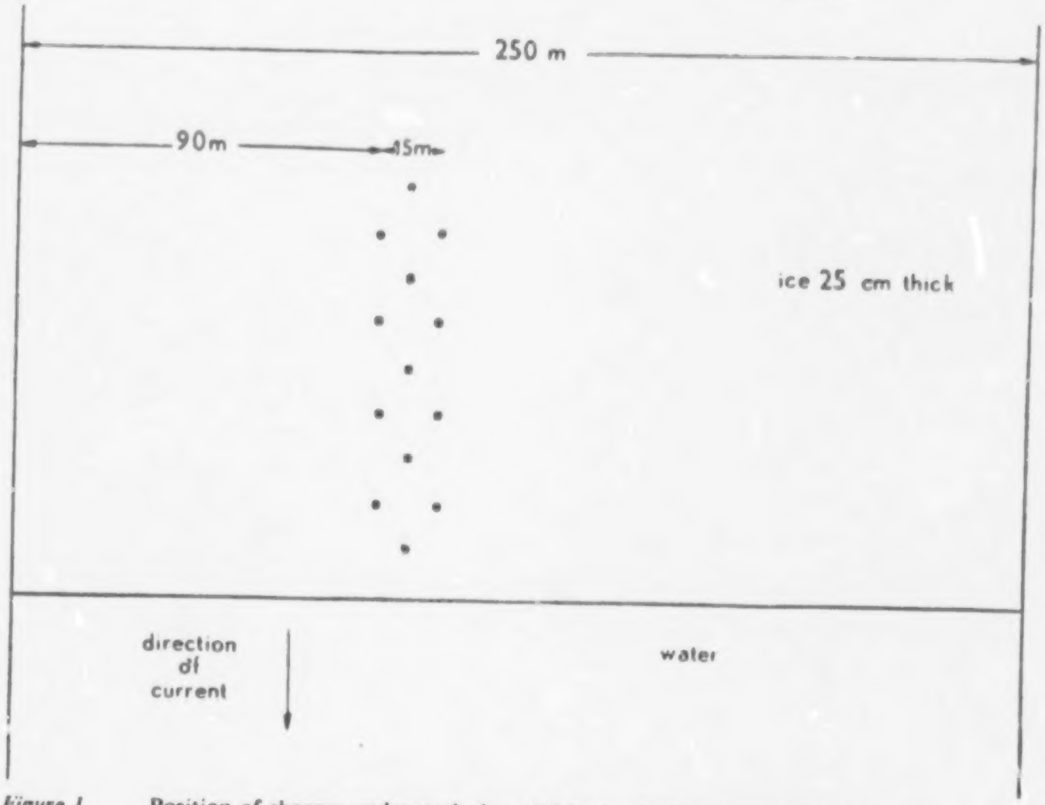

250 m
90m
15m
ice 25 cm thick
direction
of
current
water

Figure 1. Position of charges underneath the solid ice in the Waal near Opijnen.

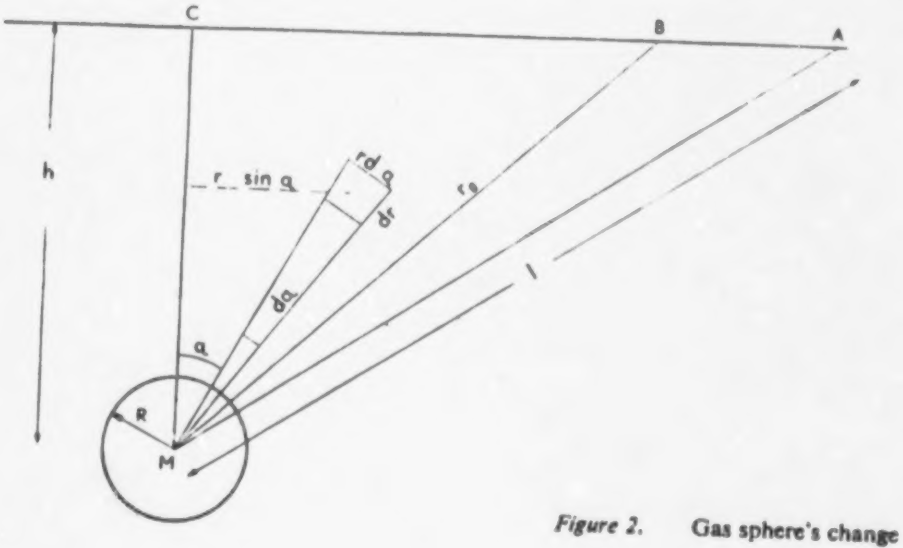

C
B
A
h
r sin a
rd a
dr
r₀
l
da
a
R
M

Figure 2. Gas sphere's change of shape.

(Van der Kley, 1965)

"Assume there is a plane surface $r\,d\alpha\,dr$ in area situated a distance of r away from M. The volume dV or the ring with radius $r \sin\alpha$ will be $2\pi r^2 \sin\alpha\, d\alpha\, dr$. The specific change in the volume of the water will be $\varepsilon = \mu\sigma$ in which

$$\mu = \frac{1}{K},$$

K being the compression modulus.

"The deformation force dW is $\frac{1}{2}\varepsilon\sigma\, dV$, in which

$$\sigma = \frac{pR^2}{r^2},$$

dV is volume of ring and p is pressure in sphere of gas with radius R. We then see that

$$dW = \tfrac{1}{2}\mu\sigma\, dV = \frac{\pi\mu p^2 R^4}{r^2} dr \sin\alpha\, d\alpha.$$

"Force is exerted until the diameter of the sphere is 1, when atmospheric pressure is reached. Then we see that

$$\begin{aligned} W &= \pi\mu p^2 R^4 \int_0^\pi \sin\alpha\, d\alpha \int_R^l \frac{dr}{r^2} = -\pi\mu p^2 R^4 \int_0^\pi \sin\alpha\, d\alpha \left.\frac{1}{r}\right|_R^l = \\ &= \pi\mu p^2 R^4 \left(\frac{l-R}{lR}\right) \int_0^\pi \sin\alpha\, d\alpha = -\pi\mu p^2 R^4 \left(\frac{l-R}{lR}\right) \left.\cos\alpha\right|_0^\pi = \\ &= -\frac{\pi\mu p^2 R^4 (l-R)}{lR}(-2) = \frac{2\pi\mu p^2 R^4 (l-R)}{lR}. \end{aligned} \qquad (1)$$

The stress in a sphere of radius 1 is $\frac{pR^2}{2}$.

"This will balance atmospheric pressure, so

$$pR^2 = l^2. \qquad (2)$$

If there is ice on top of the water (the underside of the ice is shown in Figure 2), the deformation energy will rupture it up to B.

"The stress at B will be $\frac{pR^2}{r_0^2}$.

It will have to balance C^2, which is the resistance to pressure of the ice, so

$$\frac{pR^2}{r_0^2} = C^2 \quad \text{or} \quad pR^2 = C^2 r_0^2 . \tag{3}$$

"From (2) and (3) it follows that

$$l = Cr_0 . \tag{4}$$

"According to the general law governing gases, the pressure p, the volume V, the mass m and the absolute temperature are related to one another in the following manner: $pV = mCT$ or $p\frac{4}{3}\pi R^3 = mCT = C'W$ or $W = \varphi p R^3$ Since the weight of the charge L is proportionate to the energy W, we see that $L = \delta p R^3$; and since according to (3)

$$pR^2 = C^2 r_0^2 ,$$

we see that

$$L = \delta C^2 r_0^2 R \quad \text{or} \quad R = \frac{L}{\delta C^2 r_0^2} . \tag{5}$$

"Since the weight of the charge L is proportionate to the energy W(L = λW), (3), (4) and (5) substituted in (1) gives us

$$L = \frac{2\pi\mu\lambda C^4 r_0^4 \left(Cr_0 - \dfrac{L}{\delta C^2 r_0^2} \right)}{\dfrac{Cr_0 L}{\delta C^2 r_0^2}}$$

or

$$L = \frac{2\pi\mu\lambda\delta C^6 r_0^6}{L} - 2\pi\mu\lambda C^3 r_0^3$$

or

$$L^2 + 2\pi\mu\lambda L C^3 r_0^3 - 2\pi\mu\lambda\delta C^6 r_0^6 = 0$$

$$L = \frac{-2\pi\mu\lambda C^3 r_0^3 \pm \sqrt{4\pi^2\mu^2\lambda^2 C^6 r_0^6 + 8\pi\mu\lambda\delta C^6 r_0^6}}{2} =$$

$$= \pi\mu\lambda C^3 r_0^3 \left[-1 + \sqrt{1 + \frac{2\delta}{\pi\mu\lambda}} \right] .$$

"Only the positive root is operative. The term under the root symbol is constant and greater than unity, so we may write

$$L = Ar_0^3 \tag{6}$$

"If there is ice of thickness d, the spherical pressure wave will be deflected at A and will reach the surface at C, so that a hole with radius t will be blown in the ice (see Figure 3); consequently

$$\sin i_1 = n \sin i_2, \tag{7}$$

in which n is a constant and the detonation point M seems to have moved to N. The stress along AB and AC remains unaltered.

From (7) we see that

$$\frac{b}{r_0} = \frac{nb}{l_1} \quad \text{or} \quad l_1 = l_2 = nr_0 \tag{8}$$

and that

$$t^2 = n^2 r_0^2 - (d + h + a)^2. \tag{9}$$

In the latter

$$\begin{aligned} a &= nr_0 \cos i_2 - r_0 \cos i_1 = \\ &= nr_0 \sqrt{1 - \sin^2 i_2} - h = nr_0 \sqrt{1 - \frac{\sin^2 i_1}{n^2}} - h = \\ &= r_0 \sqrt{n^2 - \sin^2 i_1} - h = r_0 \sqrt{n^2 - 1 + \cos^2 i_1} - h = \\ &= r_0 \sqrt{n^2 - 1 + \frac{h^2}{r_0^2}} - h = \sqrt{r_0^2 (n^2 - 1) + h^2} - h. \end{aligned}$$

This value for a substituted in (9) gives

$$t^2 = n^2 r_0^2 - \left[d + \sqrt{r_0^2 (n^2 - 1) + h^2}\right]^2. \tag{10}$$

In the latter, r_0 is the term from (6) $L = Ar_0^3$.

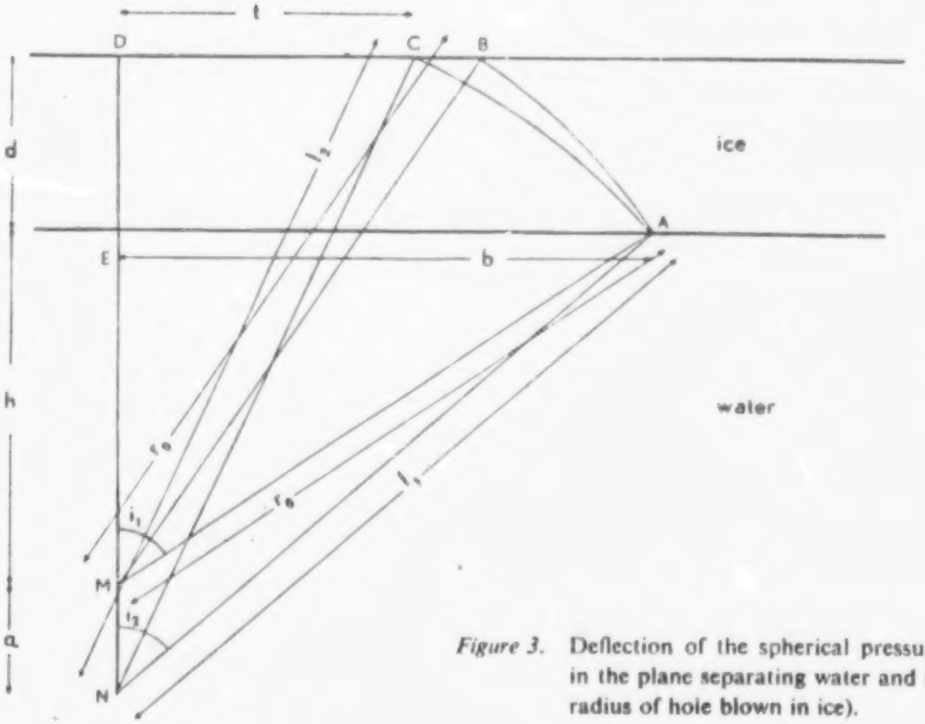

t
D
C
B
d
ice
A
E
b
h
water
l_2
r_0
r_0
l_1
i_1
M
i_2
a
N

Figure 3. Deflection of the spherical pressure wave in the plane separating water and ice (t = radius of hole blown in ice).

(Van der Kley, 1965)

"Size of charge that will just break ice from below

"To discover this, t (radius of hole blown) in (10) is made zero, so that

$$n^2 r_0^2 = \left[d + \sqrt{r_0^2(n^2 - 1) + h^2}\right]^2.$$

On working this out we see that

$$r_0^2 = h^2 + d^2(2n^2 - 1) + 2nd\sqrt{d^2(n^2 - 1) + h^2}.$$

Substituting

$$r_0 = \sqrt[3]{\frac{L}{A}}$$

(formula 6), we get the charge required (L)

$$\sqrt[3]{\left(\frac{L}{A}\right)^2} = h^2 + d^2(2n^2 - 1) + 2nd\sqrt{d^2(n^2 - 1) + h^2}. \qquad (11)$$

This formula can be used to calculate the minimum weights of charge for various h and d values required to rupture the ice.

"Double charge, called percussion charge, underneath the ice (Figure 4)

"r_1 must satisfy equation (10):

$$t^2 = n^2 r_1^2 - \left[d + \sqrt{r_1^2(n^2 - 1) + h_1^2}\right]^2$$

from this we see that r_1 can be deduced from

$$r_1^2 = (t^2 - d^2 + h_1^2 + 2d^2n^2) + 2d\sqrt{d^2n^4 - t^2 + t^2n^2 - d^2n^2 + h_1^2n^2}, \qquad (12)$$

r_2 must satisfy

$$r_2^2 = (t^2 - d^2 + h_2^2 + 2d^2n^2) + 2d\sqrt{d^2n^4 - t^2 + t^2n^2 - d^2n^2 + h_2^2n^2}. \qquad (13)$$

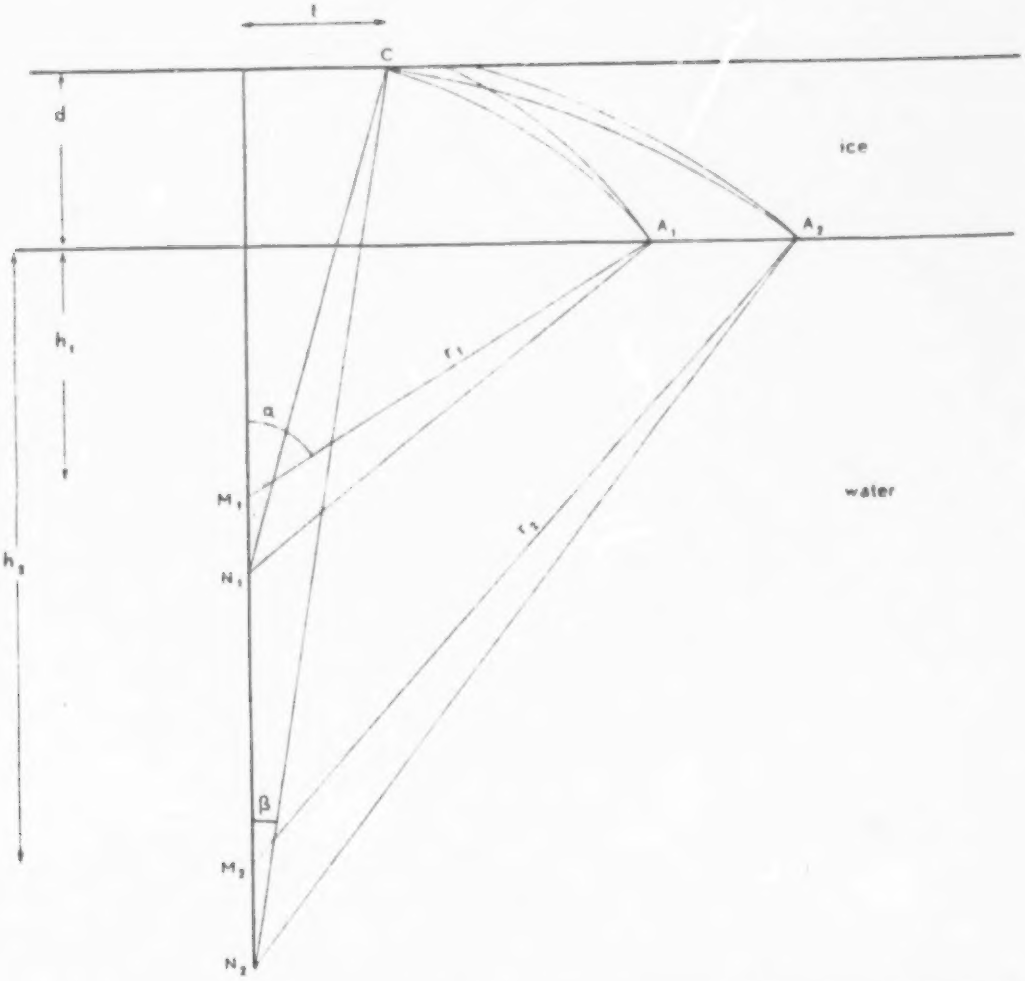

t
C
d
ice
A_1
A_2
h_1
r_1
α
M_1
N_1
water
h_2
r_2
β
M_2
N_2

Figure 4. Deflection of pressure waves in the plane between water and ice when double charges (percussion charges) are used (t = radius of hole blown in ice).

(Van der Kley, 1965)

The stress at C due to the charge L_1 is $\frac{p_2 R_2^2}{r_2^2}$.

The two stresses must balance the resistance to pressure of the ice, i.e.,

$$\frac{p_1 R_1^2}{r_1^2} + \frac{p_2 R_2^2}{r_2^2} = C^2. \tag{14}$$

The aberration due to the shock wave not reaching A_1 and A_2 simultaneously because of the difference in distance is ignored.
Formula (3) shows us that for L_1

$$p_1 R_1^2 = C^2 r_1^2$$

or

$$p_1 R_1^2 = C^2 \sqrt[3]{\left(\frac{L_1}{A}\right)^2}.$$

For L_2 we get

$$p_2 R_2^2 = C^2 \sqrt[3]{\left(\frac{L_2}{A}\right)^2}.$$

Substituting these two terms in (14) we get

$$\frac{\sqrt[3]{\left(\frac{L_1}{A}\right)^2}}{r_1^2} + \frac{\sqrt[3]{\left(\frac{L_2}{A}\right)^2}}{r_2^2} = 1 \quad \text{or} \quad \frac{\sqrt[3]{L_1^2}}{r_1^2} + \frac{\sqrt[3]{L_2^2}}{r_2^2} = \left(\sqrt[3]{A}\right)^2.$$

Substituting the values of r_1 and r_2 obtained from formulas (12) and (13) gives us the charge formula for percussion charges, viz.

$$\frac{\sqrt[3]{L_1^2}}{r_1^2} + \frac{\sqrt[3]{L_2^2}}{r_2^2} = \left(\sqrt[3]{A}\right)^2 \tag{15}$$

in which

$$r_1^2 = (t^2 - d^2 + h_1^2 + 2d^2n^2) + 2d\sqrt{d^2n^4 - t^2 + t^2n^2 - d^2n^2 + h_1^2n^2}.$$
$$r_2^2 = (t^2 - d^2 + h_2^2 + 2d^2n^2) + 2d\sqrt{d^2n^4 - t^2 + t^2n^2 - d^2n^2 + h_2^2n^2}.$$

This formula can be used for calculating the diameter (t) of the hole blown in the ice.

"Charge formula for charges placed on the ice

"The spherical pressure wave is deflected in the air/ice plane (Figure 5), as is the case with charges placed underneath the ice. The detonation point M appears to move to N. A formula analogous to (5) gives us for a charge underneath the ice

$$t^2 = n^2 r_0^2 - \left[d + \sqrt{r_0^2(n^2 - 1)}\right]^2 \tag{16}$$

r_0 being the term from (6) $L = Ar_0^3$.

"Weight of charge placed on the ice just powerful enough to break it

"To arrive at this, t (radius of hole blown in ice) is made zero in (16), so that

$$n^2 r_0^2 = \left[d + \sqrt{r_0^2(n^2 - 1)}\right]^2.$$

On working this out we get a formula analogous to (11)

$$\sqrt[3]{\left(\frac{L}{A}\right)^2} = d^2(2n^2 - 1) + 2nd\sqrt{d^2(n^2 - 1)}. \tag{17}$$

This formula can be used for calculating for various d values the minimum weights of charge just powerful enough to break the ice.

"Determining the coefficients

"The coefficients A and n can be determined by using the results of experiments reported on in
- Explosives regulation No. 427 of 1914, Engineers Corps;
- 'Clearing ice with dynamite and guncotton' by G. J. Blaauw, from 'Minutes of meeting on 14th November 1871', by Royal Institute of Engineers Journal, Institute year 1871-1872;
- Reports on experiments conducted by the Rijkswaterstaat and the Army on Veluwemeer in 1961 and 1963 (for internal use only).

"The following formulae were used for calculating the A coefficients:
(6) and (10) for single charges under the ice;
(6) and (15) for double charges under the ice;
(6) and (16) for charges on the ice.

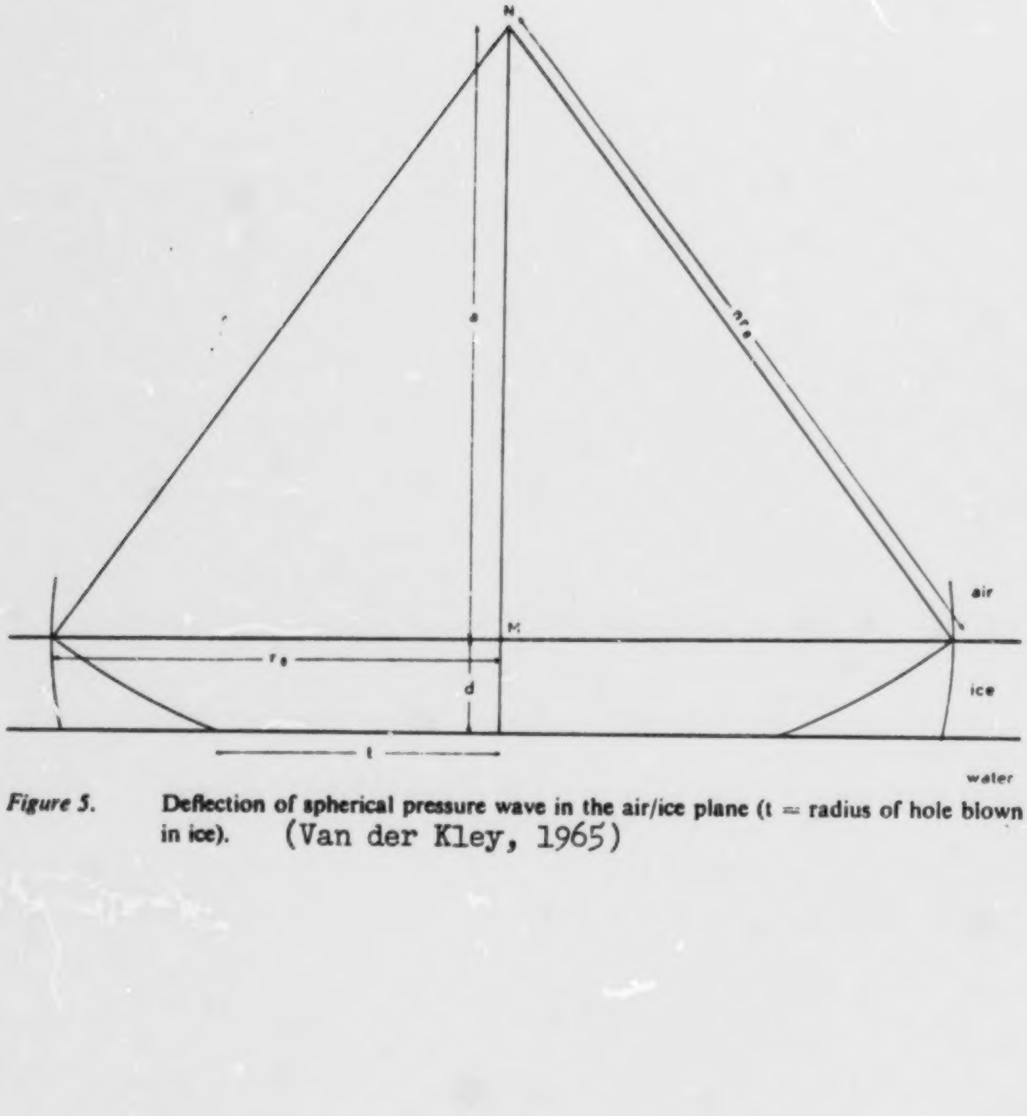

N
a
nr_e
air
M
r_e
d
ice
t
water

Figure 5. **Deflection of spherical pressure wave in the air/ice plane (t = radius of hole blown in ice).** (Van der Kley, 1965)

"The value at which the least spreading occurred in coefficient A was taken as the deflection coefficient n and after the elimination of the dependence on the measured quantities."

Tabular values for tests to determine A at n = 1.1 and 1.7 are given for several types of explosives.

"Summary of results

"Single charge under the ice

$$t^2 = n^2 \sqrt[3]{\frac{L^2}{A^2}} - \left[d + \sqrt{\sqrt[3]{\frac{L^2}{A^2}}(n^2 - 1) + h^2} \right]^2$$

in which

t = radius of hole blown in metres
n = deflection coefficient (here taken as 1.1)
L = weight of charge in Kgs
A = constant
d = thickness of ice in metres
h = distance from charge to under-surface of ice in metres.

Value of A for

Dutch TNT	0.066
American TNT	0.084
Guncotton	0.047
Dynamite	0.045
Ammonal	0.075
Gunpowder	0.146

The connection between the weight of charge L, the diameter of the hole blown and the thickness of the ice when Dutch TNT is used at various depths below the ice is ... given in tables 9 to 17.

"Double charge under the ice

$$r_1^2 = (t^2 - d^2 + h_1^2 + 2d^2n^2) + 2d\sqrt{d^2n^4 - t^2 + t^2n^2 - d^2n^2 + h_1^2n^2},$$

$$r_2^2 = (t^2 - d^2 + h_2^2 + 2d^2n^2) + 2d\sqrt{d^2n^4 - t^2 + t^2n^2 - d^2n^2 + h_2^2n^2},$$

$$\frac{\sqrt[3]{L_1^2}}{r_1^2} + \frac{\sqrt[3]{L_2^2}}{r_2^2} = \sqrt[3]{A^2}$$

in which

t = diameter of hole blown in metres
n = deflection coefficient (here taken as 1.1)
d = thickness of ice in metres
h_1 = distance from main charge to under-surface of ice

Table 9. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 0.00 metre below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250	1.56	1.45	1.21	0.79	0.04				
0.500	1.96	1.86	1.64	1.40	1.03				
0.750	2.25	2.14	1.94	1.72	1.41				
1	2.47	2.37	2.18	1.96	1.69				
2	3.12	3.02	2.84	2.65	2.42	0.07			
3	3.57	3.47	3.29	3.12	2.91	1.48			
4	3.93	3.83	3.66	3.49	3.29	2.06			
5	4.23	4.13	3.96	3.80	3.61	2.48			
7.50	4.84	4.75	4.58	4.42	4.24	3.25	1.07		
10	5.33	5.24	5.07	4.92	4.75	3.83	2.18		
20	6.72	6.62	6.46	6.32	6.16	5.37	4.20	2.12	
30	7.69	7.59	7.44	7.30	7.15	6.40	5.38	3.86	
40	8.46	8.37	8.22	8.08	7.93	7.22	6.27	4.96	2.80
50	9.12	9.02	8.87	8.73	8.59	7.90	7.00	5.80	4.04
75	10.44	10.34	10.19	10.06	9.92	9.26	8.44	7.39	6.01
100	11.49	11.39	11.24	11.11	10.97	10.34	9.56	8.59	7.37
200	14.47	14.38	14.23	14.10	13.97	13.38	12.67	11.85	10.87
300	16.56	16.47	16.33	16.20	16.07	15.49	14.83	14.06	13.17
400	18.23	18.14	18.00	17.87	17.74	17.18	16.53	15.80	14.96
500	19.64	19.55	19.40	19.28	19.15	18.59	17.96	17.26	16.45
750	22.48	22.39	22.25	22.12	22.00	21.45	20.85	20.18	19.43
1 000	24.74	24.65	24.51	24.39	24.26	23.73	23.14	22.48	21.77
10 000	53.31	53.22	53.08	52.96	52.84	52.35	51.83	51.29	50.72

(Van der Kley, 1965)

Table 10. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 0.25 metre below the under-surface of the ice.

L	d = 0.00	d 0.20	d 0.50	d 0.75	d 1.00	d = 2.00	d 3.00	d 4.00	d = 5.00
0.250	1.54	1.42	1.17	0.82					
0.500	1.95	1.84	1.62	1.35	0.96				
0.750	2.23	2.13	1.92	1.68	1.37				
1	2.46	2.36	2.16	1.94	1.66				
2	3.11	3.01	2.82	2.63	2.40				
3	3.56	3.46	3.28	3.10	2.89	1.43			
4	3.92	3.82	3.65	3.48	3.28	2.02			
5	4.22	4.12	3.95	3.79	3.60	2.45			
7.50	4.84	4.74	4.57	4.41	4.24	3.24	1.00		
10	5.32	5.23	5.06	4.91	4.74	3.81	2.15		
20	6.71	6.62	6.46	6.31	6.15	5.36	4.19	2.08	
30	7.68	7.59	7.44	7.29	7.14	6.40	5.37	3.85	
40	8.46	8.36	8.21	8.07	7.92	7.21	6.26	4.95	2.77
50	9.11	9.02	8.87	8.73	8.58	7.89	7.00	5.79	4.02
75	10.43	10.34	10.19	10.05	9.91	9.26	8.43	7.38	6.00
100	11.48	11.39	11.24	11.11	10.97	10.33	9.55	8.58	7.36
200	14.47	14.38	14.23	14.10	13.97	13.37	12.67	11.84	10.86
300	16.56	16.47	16.32	16.20	16.07	15.49	14.82	14.06	13.17
400	18.23	18.14	17.99	17.87	17.74	17.17	16.53	15.80	14.96
500	19.64	19.55	19.40	19.28	19.15	18.59	17.96	17.25	16.45
750	22.48	22.39	22.24	22.12	22.00	21.45	20.85	20.17	19.42
1 000	24.74	24.65	24.51	24.39	24.26	23.72	23.13	22.48	21.77
10 000	53.31	53.22	53.08	52.96	52.84	52.34	51.83	51.29	50.72

(Van der Kley, 1965)

Table 11. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 0.50 metre below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250	1.48	1.34	1.03	0.56					
0.500	1.90	1.78	1.53	1.22	0.74				
0.750	2.19	2.08	1.85	1.59	1.23				
1	2.42	2.31	2.09	1.86	1.55				
2	3.08	2.97	2.78	2.58	2.33				
3	3.53	3.43	3.24	3.06	2.84	1.28			
4	3.90	3.79	3.61	3.44	3.23	1.92			
5	4.20	4.10	3.92	3.75	3.56	2.38			
7.50	4.82	4.72	4.55	4.39	4.20	3.18	0.75		
10	5.31	5.21	5.04	4.88	4.71	3.77	2.05		
20	6.70	6.60	6.44	6.30	6.13	5.33	4.14	1.98	
30	7.67	7.58	7.42	7.28	7.12	6.37	5.34	3.79	
40	8.45	8.35	8.20	8.06	7.91	7.19	6.24	4.91	2.70
50	9.10	9.01	8.85	8.72	8.57	7.88	6.97	5.76	3.97
75	10.42	10.33	10.18	10.04	9.90	9.24	8.41	7.36	5.96
100	11.48	11.38	11.23	11.10	10.96	10.32	9.54	8.57	7.34
200	14.46	14.37	14.22	14.09	13.96	13.36	12.66	11.83	10.85
300	16.56	16.46	16.32	16.19	16.06	15.48	14.82	14.05	13.16
400	18.22	18.13	17.99	17.86	17.73	17.17	16.52	15.79	14.95
500	19.63	19.54	19.40	19.27	19.14	18.59	17.96	17.24	16.44
750	22.48	22.38	22.24	22.12	21.99	21.45	20.84	20.17	19.42
1 000	24.74	24.65	24.50	24.38	24.26	23.72	23.13	22.48	21.76
10 000	53.31	53.22	53.08	52.96	52.84	52.35	51.83	51.29	50.72

(Van der Kley, 1965)

Table 12. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 0.75 metre below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250	1.37	1.19	0.76						
0.500	1.82	1.67	1.37	0.99					
0.750	2.12	1.99	1.72	1.42	0.97				
1	2.36	2.23	1.99	1.72	1.36				
2	3.03	2.91	2.70	2.48	2.22				
3	3.49	3.38	3.18	2.98	2.75	0.99			
4	3.86	3.75	3.56	3.37	3.16	1.75			
5	4.16	4.06	3.88	3.70	3.49	2.24			
7.50	4.78	4.68	4.51	4.34	4.15	3.09			
10	5.28	5.18	5.00	4.84	4.66	3.69	1.88		
20	6.68	6.58	6.41	6.26	6.10	5.28	4.07	1.79	
30	7.65	7.56	7.40	7.25	7.10	6.34	5.29	3.71	
40	8.43	8.33	8.18	8.04	7.88	7.16	6.19	4.84	2.56
50	9.08	8.99	8.83	8.70	8.55	7.85	6.93	5.71	3.89
75	10.41	10.31	10.16	10.02	9.88	9.22	8.38	7.32	5.91
100	11.46	11.37	11.22	11.08	10.94	10.30	9.51	8.53	7.29
200	14.45	14.36	14.21	14.08	13.95	13.35	12.64	11.81	10.82
300	16.55	16.45	16.31	16.18	16.05	15.47	14.80	14.03	13.14
400	18.22	18.12	17.98	17.85	17.72	17.16	16.51	15.77	14.93
500	19.63	19.53	19.39	19.26	19.13	18.58	17.94	17.23	16.43
750	22.47	22.38	22.23	22.11	21.98	21.44	20.83	20.16	19.41
1 000	24.73	24.64	24.50	24.38	24.25	23.71	23.12	22.47	21.75
10 000	53.31	53.21	53.07	52.96	52.84	52.34	51.82	51.28	50.72

(Van der Kley, 1965)

Table 13. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 1.00 metre below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250	1.20	0.95							
0.500	1.69	1.51	1.12	0.53					
0.750	2.01	1.86	1.54	1.16	0.43				
1	2.26	2.12	1.83	1.51	1.05				
2	2.95	2.82	2.59	2.35	2.06				
3	3.43	3.31	3.09	2.88	2.63	0.26			
4	3.80	3.68	3.48	3.28	3.05	1.48			
5	4.11	4.00	3.80	3.62	3.40	2.04			
7.50	4.74	4.63	4.45	4.27	4.07	2.95			
10	5.24	5.13	4.95	4.78	4.60	3.59	1.61		
20	6.64	6.54	6.37	6.22	6.05	5.21	3.96	1.49	
30	7.62	7.52	7.36	7.22	7.06	6.28	5.21	3.58	
40	8.40	8.30	8.15	8.00	7.85	7.11	6.13	4.75	2.36
50	9.06	8.96	8.81	8.67	8.52	7.80	6.88	5.63	3.76
75	10.39	10.29	10.14	10.00	9.86	9.18	8.34	7.27	5.83
100	11.44	11.35	11.19	11.06	10.92	10.27	9.48	8.49	7.24
200	14.44	14.34	14.19	14.06	13.93	13.33	12.62	11.78	10.79
300	16.54	16.44	16.29	16.17	16.03	15.45	14.78	14.00	13.11
400	18.20	18.11	17.96	17.84	17.71	17.14	16.49	15.75	14.91
500	19.62	19.52	19.38	19.25	19.12	18.56	17.93	17.21	16.41
750	22.46	22.37	22.22	22.10	21.97	21.42	20.82	20.14	19.39
1 000	24.72	24.63	24.49	24.36	24.24	23.70	23.11	22.46	21.74
10 000	53.30	53.21	53.07	52.95	52.83	52.34	51.82	51.28	50.71

(Van der Kley, 1965)

Table 14. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 2.00 metres below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250									
0.500									
0.750	1.03	0.34							
1	1.46	1.08							
2	2.39	2.17	1.74	1.21					
3	2.96	2.77	2.43	2.07	1.60				
4	3.38	3.21	2.91	2.61	2.25				
5	3.73	3.57	3.30	3.03	2.71				
7.50	4.41	4.27	4.03	3.80	3.53	1.87			
10	4.94	4.81	4.58	4.37	4.14	2.79			
20	6.41	6.29	6.10	5.92	5.72	4.74	3.18		
30	7.42	7.31	7.13	6.96	6.78	5.91	4.67	2.59	
40	8.22	8.11	7.94	7.78	7.61	6.79	5.70	4.09	
50	8.89	8.79	8.62	8.46	8.30	7.52	6.50	5.10	2.79
75	10.24	10.14	9.97	9.83	9.67	8.95	8.05	6.89	5.30
100	11.31	11.21	11.05	10.90	10.75	10.07	9.23	8.18	6.83
200	14.33	14.23	14.08	13.94	13.80	13.18	12.44	11.58	10.54
300	16.44	16.35	16.20	16.06	15.93	15.33	14.64	13.84	12.92
400	18.12	18.03	17.88	17.75	17.61	17.03	16.37	15.61	14.75
500	19.54	19.44	19.29	19.17	19.03	18.46	17.82	17.09	16.26
750	22.39	22.30	22.15	22.03	21.90	21.34	20.72	20.04	19.27
1 000	24.66	24.57	24.42	24.30	24.17	23.63	23.03	22.36	21.64
10 000	53.27	53.18	53.04	52.92	52.80	52.31	51.79	51.24	50.68

(Van der Kley, 1965)

Table 15. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 3.00 metres below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250									
0.500									
0.750									
1									
2	0.85								
3	1.93	1.53	0.26						
4	2.54	2.23	1.64	0.79					
5	2.98	2.73	2.25	1.73	0.87				
7.50	3.80	3.60	3.24	2.88	2.45				
10	4.41	4.22	3.91	3.61	3.27				
20	6.01	5.86	5.62	5.40	5.15	3.86	1.15		
30	7.08	6.94	6.73	6.53	6.31	5.25	3.65		
40	7.91	7.79	7.58	7.40	7.20	6.24	4.92	2.72	
50	8.61	8.49	8.29	8.11	7.93	7.04	5.85	4.12	
75	10.00	9.88	9.70	9.53	9.36	8.56	7.55	6.22	4.30
100	11.09	10.98	10.80	10.64	10.48	9.73	8.81	7.64	6.11
200	14.16	14.05	13.89	13.74	13.60	12.93	12.16	11.23	10.13
300	16.29	16.19	16.03	15.89	15.75	15.12	14.40	13.57	12.60
400	17.98	17.88	17.73	17.59	17.45	16.85	16.16	15.38	14.48
500	19.41	19.31	19.16	19.02	18.89	18.30	17.63	16.88	16.03
750	22.28	22.18	22.03	21.90	21.77	21.20	20.57	19.86	19.08
1 000	24.56	24.47	24.32	24.19	24.06	23.50	22.89	22.21	21.47
10 000	53.23	53.13	52.99	52.87	52.75	52.26	51.73	51.19	50.62

(Van der Kley, 1965)

Table 16. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 4.00 metres below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250									
0.500									
0.750									
1									
2									
3									
4									
5	1.38	0.29							
7.50	2.73	2.36	1.62	0.19					
10	3.52	3.24	2.74	2.20	1.43				
20	5.40	5.20	4.88	4.58	4.24	2.22			
30	6.57	6.40	6.13	5.88	5.61	4.22	1.46		
40	7.46	7.30	7.06	6.83	6.59	5.42	3.63		
50	8.19	8.05	7.82	7.61	7.38	6.32	4.84	2.20	
75	9.64	9.51	9.30	9.11	8.91	8.00	6.82	5.20	2.36
100	10.77	10.64	10.44	10.27	10.08	9.24	8.20	6.86	4.98
200	13.91	13.79	13.62	13.46	13.30	12.59	11.74	10.74	9.54
300	16.08	15.97	15.80	15.65	15.50	14.84	14.07	13.18	12.15
400	17.79	17.68	17.52	17.38	17.23	16.59	15.87	15.04	14.10
500	19.23	19.12	18.96	18.82	18.68	18.06	17.37	16.58	15.69
750	22.12	22.02	21.87	21.73	21.60	21.01	20.35	19.62	18.81
1 000	24.42	24.32	24.17	24.04	23.90	23.33	22.70	22.00	21.24
10 000	53.16	53.07	52.92	52.80	52.68	52.18	51.66	51.11	50.53

(Van der Kley, 1965)

Table 17. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 5.00 metres below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250									
0.500									
0.750									
1									
2									
3									
4									
5									
7.50									
10	1.85	1.08							
20	4.48	4.21	3.74	3.28	2.72				
30	5.84	5.62	5.27	4.94	4.57	2.38			
40	6.83	6.64	6.33	6.05	5.74	4.16			
50	7.62	7.45	7.16	6.91	6.64	5.30	3.16		
75	9.16	9.00	8.76	8.54	8.31	7.23	5.78	3.54	
100	10.34	10.20	9.97	9.77	9.56	8.60	7.37	5.73	3.05
200	13.58	13.46	13.26	13.09	12.92	12.13	11.21	10.10	8.74
300	15.79	15.68	15.49	15.34	15.17	14.46	13.63	12.68	11.55
400	17.53	17.42	17.25	17.10	16.94	16.26	15.49	14.61	13.60
500	18.99	18.88	18.71	18.57	18.42	17.76	17.03	16.20	15.26
750	21.92	21.81	21.65	21.51	21.37	20.75	20.07	19.31	18.46
1 000	24.23	24.13	23.97	23.84	23.70	23.10	22.45	21.73	20.94
10 000	53.08	52.98	52.84	52.72	52.60	52.09	51.56	51.01	50.42

(Van der Kley, 1965)

h_2 = distance from percussion charge to under-surface of ice
L_1 = weight of main charge in Kgs
L_2 = weight of percussion charge in Kgs
A = constant.

the values given ... (above) can be taken for the constant A.

"Charge on the ice

$$t^2 = n^2\sqrt[3]{\frac{L^2}{A^2}} - \left[d + \sqrt{\sqrt[3]{\frac{L^2}{A^2}}(n^2 - 1)}\right]^2$$

in which

t = diameter of hole blown in metres
n = deflection coefficient (here taken as 1.7)
L = weight of charge in Kgs
A = constant
d = thickness of ice in metres.

Values for A

Dutch TNT	0.352
American TNT	0.343
Mine M 26	0.172
Plastic explosive	0.135
TNT (drilling cartridge)	1.093

The connection between the weight of charge L, the diameter of the hole blown and the thickness of the ice is shown for Dutch TNT ... in Table 18.

"Minimum charge needed to break through the ice

"Charge under the ice

$$L = A\sqrt{\left[h^2 + d^2(2n^2 - 1) + 2nd\sqrt{d^2(n^2 - 1) + h^2}\right]^3}$$

in which

L = weight of charge that will just break through the ice, in Kgs
n = deflection coefficient (here taken as 1.1)
d = thickness of ice in metres
h = distance from charge to under-surface of ice in metres
A = constant

"The data given in ... ('single charge under the ice') can be adopted for the constant A.

"The connection between the minimum charge needed to break through the ice and the thickness of the ice with charges at various depths and using Dutch TNT is ... given in Table 19.

Table 18. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed on the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.125	0.71	0.27							
0.250	0.89	0.52							
0.500	1.12	0.78							
0.750	1.29	0.95							
1	1.42	1.09							
2	1.78	1.47	0.69						
3	2.04	1.74	1.06						
4	2.25	1.94	1.31						
5	2.42	2.12	1.51	0.56					
7.50	2.77	2.47	1.90	1.19					
10	3.05	2.76	2.21	1.57					
20	3.84	3.55	3.04	2.51	1.79				
30	4.40	4.11	3.62	3.12	2.50				
40	4.84	4.56	4.07	3.59	3.02				
50	5.22	4.93	4.45	3.99	3.45				
75	5.97	5.69	5.22	4.77	4.27				
100	6.57	6.29	5.82	5.39	4.91	1.75			
200	8.28	8.00	7.55	7.14	6.70	4.36			
300	9.48	9.20	8.75	8.35	7.93	5.81	1.64		
400	10.44	10.16	9.71	9.32	8.90	6.89	3.72		
500	11.24	10.96	10.52	10.13	9.72	7.78	4.96		
750	12.87	12.59	12.15	11.77	11.37	9.53	7.10	2.84	
1 000	14.16	13.88	13.45	13.07	12.68	10.90	8.65	5.37	
10 000	30.51	30.24	29.81	29.45	19.09	27.56	25.89	24.07	22.06

(Van der Kley, 1965)

Table 19. Quantity of L (Dutch TNT in Kgs), placed h metres below the under-surface of ice d metres thick that will just break through the ice.

d	h = 0.00	h = 0.25	h = 0.50	h = 0.75	h = 1.00	h = 2.00	h = 3.00	h = 4.00	h = 5.00
0.00	0.000	0.001	0.008	0.028	0.066	0.528	1.782	4.224	8.250
0.10	0.000	0.003	0.015	0.042	0.091	0.620	1.986	4.583	8.808
0.20	0.002	0.008	0.025	0.061	0.121	0.724	2.206	4.964	9.392
0.30	0.007	0.015	0.040	0.086	0.159	0.840	2.444	5.367	10.004
0.40	0.016	0.028	0.061	0.118	0.204	0.969	2.700	5.793	10.645
0.50	0.031	0.046	0.088	0.157	0.258	1.111	2.975	6.244	11.315
0.75	0.105	0.129	0.194	0.296	0.440	1.535	3.751	7.482	13.124
1.00	0.250	0.282	0.371	0.511	0.703	2.066	4.666	8.890	15.136
2.00	1.998	2.063	2.253	2.558	2.969	5.622	10.032	16.532	25.499
3.00	6.743	6.841	7.131	7.605	8.250	12.397	18.975	28.175	40.326
4.00	15.982	16.113	16.503	17.144	18.026	23.751	32.735	44.977	60.711
5.00	31.216	31.379	31.868	32.676	33.792	41.127	52.659	68.197	87.846

Table 20. Quantity of L (Dutch TNT in Kgs), placed on ice d metres thick that will just break through the ice.

d	L	d	L	d	L
0.00	0.000	0.40	0.655	2.00	81.860
0.10	0.010	0.50	1.279	3.00	276.28
0.20	0.082	0.75	4.317	4.00	654.88
0.30	0.276	1.00	10.232	5.00	1279.1

(Van der Kley, 1965)

"Charge on the ice

$$L = Ad^3\left(n + \sqrt{n^2 - 1}\right)^3$$

in which

L = weight of charge that will just break through the ice, in Kgs
n = deflection coefficient (here taken as 1.7)
d = thickness of ice in metres
A = constant.

The data given ... (above - charge on the ice) can be adopted for the constant A.

"The connection between the minimum charge needed to break through the ice and the thickness of the ice is given ... in Table 20.

"How explosives can be used for removing ice

"Cost of breaking solid sheet ice

"... The daily 'production' of an ice-breaker in normal river ice (30-40 cms thick) may be set at 900 metres of river 300 metres wide, i.e. an area of 27 hectares. The average cost may be set at 190 Dutch guilders per 'breaking' hour. Assuming that breaking goes on for 9 hours daily, this works out at 70 guilders per hectare.

"Cost of blowing up solid sheet ice

"Charges placed on the ice

"The simpliest employment in the M 26 mine. When placed on ice 40 cms thick it will blow a hole in it with a radius of 2.25 metres. The area of ice thus destroyed is $\pi(2.25)^2$ squares metres. If the holes are located at the corners of a network of squares of such a size that the holes touch each other, the total area destroyed will be $4/\pi:\pi 2.25^2 = 20.25\ m^2$. Taking 45 guilders as the cost of a mine, this works out 2.22 guilders per square metre. The mines are comparatively easy to lay. It may be assumed that one man can lay and detonate 12 mines per hour if the ice is smooth and easy to move about on. At a wage of 5 guilders per hour that means another 0.01 guilder per square metre.

"About 125 men would be required to break the same area in one day as a single icebreaker (i.e. 900 x 300 square metres), because

$$\frac{900 \times 300}{9 \times 20.25 \times 12} = \text{approx. } 125.$$

"The cost per hectare is 10.000 x 2.23 guilders = 22.300 guilders. That is 320 times as expensive as an ice-breaker.

"The cost can be cut and the number of men required can be reduced considerably by blowing continuous swaths in the ice so that large floes can float away and be reduced by ice-breakers. The holes would have to overlap far enough to make the ice self-releasing and incapable of getting caught. This will be difficult to achieve in practice.

"Charges underneath the ice

"Explosives are most effective when charges are placed immediately below the ice.... The quantity of explosive per square metre of ice blown out increases as the quantity of explosive rises. If the ice is 40 cms thick, 0.75 Kgs TNT must be detonated on it to make the hole through which the main charge must be lowered. This should be added to the main charge. It will then be seen that the total quantity of explosive required per square metre of ice blown up is at its lowest when a main charge of 2 Kgs TNT is used. The total quantity of explosive required is then 2.75 Kgs. With TNT at 4 guilders a Kg the cost of blowing up a square metre of ice works out at 0.33 guilders, the cost of labour being negligible. The cost of clearing one hectare would be 3.300 guilders, i.e. 47 times as much as it would cost to use ice-breakers for the same area. It may be assumed that one man would be able to set off 8 charges per hour on the ice or 6 charges under the ice if it is smooth and easy to move about on. By this method 260 men would be required to break the same area of ice in one 9-hour day as an ice breaker could break, i.e. over 2 times as many as would be needed for detonating charges placed on the ice.

"Clearing ice barriers

"Ice barriers may form under certain circumstances in both the upper and the lower reaches of the rivers due to ice floes sliding under a sheet of ice that is anchored along the sides. The water level may rise, depending on the thickness of the ice-jam and the extent to which the water is prevented from running away. Sometimes the mass of ice is so loosely packed that huge quantities shoot to the surface as soon as breaking operations start. The operation consists largely in cracking the solid top layer to allow the ice below it to reach the surface and float away.... Though it is sometimes slow work, it is not difficult. Breaking by means of ice-breakers is again the best and most economical method.

"If the ice piles up so much that it prevents the water from getting away and the level is in danger of rising, the obstruction is called an ice dam. They may reach the bottom and may extend along a considerable stretch of the river. They may be as much as 6 metres thick and their downstream ends may project several metres above the water. The water level downstream is usually low, due to the obstruction, and the strong current flowing underneath the dam may cause sand to be moved and sandbanks to form. Breaking is accomplished by attacking the ice from the downstream end; large lumps are broken off until the ice starts moving. It may take as long as three days to do this. The work is not entirely lacking in hazards, because the downstream edge sticks several metres straight up out of the water. There is also the danger of the vessels running aground, owing to sandbanks that may have formed, reducing their manoeuvreability.

"Recourse may be had to various expedients when attempting to clear ice dams with explosives. Charges can be placed on the ice. If they are to be at all effective, they should shatter the ice right to the bottom of the dam. But that requires very heavy charges; 700 Kgs TNT would be needed for a dam 4 metres thick. Very much less explosive is required when M 26 mines (8.5 Kgs TNT) are employed.

"Another method is to detonate charges underneath the ice. According to ... (Table 9) an ice dam 4 metres thick would require a charge weighing anything between 10 and 20 Kgs. The difficulty lies in making a hole big enough to take a charge of that size. A hole may be hacked in the ice with a chopper or small charges can be detonated on the ice, but the greatest depth attainable by such means is about 1 metre. A 300 Kg charge of TNT or 16 M 26 mines (13.5 Kgs TNT) would be needed to smash the remaining 3 metres. The foregoing explains why attempts to clear ice dams by means of explosives have so far not been very successful. The charges were too light to shatter the ice right down to the bottom of the dam, no matter whether they were placed on the ice or in holes in the ice.

"There are serious objections to using explosives in the manner described above. The detonation of very heavy charges may damage buildings or structures in the vicinity. That may compel us to restrict the number of charges detonated simultaneously, even when using M 26 mines. After detonation, ice-breakers would have to go into action to reduce any pieces loosened and to break off large portions of the dam. It would undoubtedly have been weakened by such treatment, but then the difficulty would arise of deciding whether further charges should be set off and whether such a step would endanger the lives of those engaged in the work.

"Consequently, it is advisable to set off as large a number of mines as possible simultaneously when they are being used in groups, because it may be dangerous to go on the dam after they have been detonated."

DYNAMITE, AMMONITE, BLACK POWDER, & MISCELLANEOUS EXPLOSIVES

Reports of ice jam blasting, pertaining primarily to dynamite, are included here. Some reports using explosives such as ammonite or black powder are also summarized. Finally, reports which do not state the explosive type are given.

Straight commercial dynamite is principally used as a land clearing and cratering charge. A number 6 commercial cap (electric or nonelectric) is the smallest required for detonation. The relative effectiveness as an external charge and velocity of detonation (fps) for 40, 50, and 60% (available nitroglycerine) charges are listed below.

Comp. (%)	RE	VD (fps)
40	0.65	15,000
50	0.79	18,000
60	0.83	19,000

Value as a cratering charge is good, as is water resistance, if fired within 24 hours.

Ammonia commercial dynamite has the same principal uses and detonation is similar to straight dynamite. Additional characteristics are listed below.

Comp. (%)	RE	VD (fps)
40	0.41	9,000
50	0.46	11,000
60	0.53	12,000

Its value as a cratering charge is excellent, but water resistance is poor.

Gelatin Dynamite is principally used for land clearing and is detonated with a number 6 commercial cap. Its value as a cratering charge is rated as good, intensity of poisonous fumes is slight, and water resistance is good. Additional data is shown below:

Comp. (%)	RE	VD (fps)
40	0.42	8,000
50	0.47	9,000
60	0.76	16,000

Military dynamite (M1) is used principally for quarrying and rock cuts, has a relative effectiveness of 0.92 and velocity of detonation of 20,000 fps. Its value as a cratering charge and water resistance are rated as good (Department of the Army, 1962).

Olmstead (1955) reported on an attempt to remove an ice jam on the Niagara River.

> "The major ice jams ... were in the river below the Falls and the scope of this report is limited to that area."

Under conflicting view points as to what means, if any, should be used to combat the ice, "a demolition contractor arrived with a crew of 7 men. The Air Force provided two helicopters for placing charges in the ice jam. Three sets of ranges were installed to check movement of the ice field....

> "... The first charge, 25 pounds of dynamite, was detonated ... with no appreciable effect. The second charge of 25 pounds was detonated ... with no apparent effect....

> "... The opinion was expressed that blasting might force ice and/or water onto the lowlands on the Canadian side, endangering approximately 100 buildings in the area."

> On the following day, "... 15 charges in units of 25, 50, 75, and 150 pounds were detonated.... In some cases, a hole was made with a 25 pound charge and then a larger charge was detonated in the same hole. At 1630 hours, no change was evident in the main ice jam as determined by the range stakes, although some of the slush ice adhering to the lower edge of the main jam had been dislodged....

> "... It was agreed that further dynamiting would have little, if any, effect...."

> "... There appears to be no practicable plan of improvement which would eliminate ice jams on the Lower Niagara River; therefore, a damage survey to establish economic justification is deemed unnecessary."

In other sections of this report, Foulds (1967) describes the effects of an ice boom, control structure, and icebreakers to prevent and remove ice jams on the Niagara.

Conditions which formed the ice jam reported by Olmstead were similar to those found by Dunlap (1909). He reports that the ice jam was removed using large quantities of dynamite. Details of blasting operations are not included.

Carsley (1947) describes a method of blasting river ice near Saginaw Bay (Lake Huron).

> "They picked one cartridge of dynamite ... tied a rolling hitch near one end, passed the twine to the other end of the cartridge, and tied two half hitches. They then measured off 20 in. from the half hitches, picked up another cartridge, and tied the rolling hitch and the half hitches.... As each cartridge was tied, it was placed carefully in the empty case so that ... later it could be handled without becoming entangled."
>
> "The first hole was chopped at an angle so that the 40-ft. running pole could be placed under the ice. The other holes were chopped in a triangular shape with vertical sides. They were spaced on approximately 35-ft. centers, at a distance of about 20 ft. from the river bank."
>
> "In preparing a blast the 40-ft. running pole was inserted into the first hole and pushed toward the second hole. As the forward end of the running pole approached the second hole, it was caught with the large, loopy hook on the short pole and pulled into line. After the running pole was in place under the second hole, the pole with the short hook was put into the third hole and brought up against the running pole, which was then pulled to the third hole. A loopy-hook pole was used to hold the running pole in place under the third hole while the short-hook pole was moved to the fourth hole, where the procedure was repeated. In this manner the running pole was advanced under the ice in line with the holes....
>
> "As the running pole was moved along under the ice, the ½-in. rope attached to the pole followed it into the first hole and under the ice, like a thread follows a needle. After the running pole passed the third hole, the sled carrying the explosives was brought to the first hole, and the binder twine on the first cartridge was tied to the ½-in. rope. Then one of the crew went to the third hole, where he used the small hooked pole to pull up the rope lying beneath the ice at that point. As the man pulled the rope ... (another) fed the string of cartridges into the first hole. When the end of the rope and the string of cartridges tied to it came out at the third hole, the man stopped pulling." At this point the binder twine was cut "and securely anchored (to) the section of the explosives string which was under the ice....
>
> "The crew continued the above procedures until they had blasted approximately one-half the distance planned for that day. They then moved to the opposite side of the river and repeated the loading and firing operations. This blasting of the ice in two parallel sections resulted in excellent breakage, not only at and around the area of the banks but also in the center of the river ice.
>
> "... I would estimate that this crew of four fired two holes every 15 minutes after the running pole had been passed through the first hole. This represented 70 linear feet of broken ice....

"In blasting this 2-ft. thick ice no broken particles were thrown to cause damage to properties located along both banks of the river."

Ice jams have plagued the Rochester area of the Genesee River for many years. Dintruff (1946) describes removing an ice jam there with dynamite. In 1945 an ice jam developed at a location known as the Court Street dam.

"The jam of ice at Court Street dam caused a serious situation because it had closed off two of the four spillways. Investigations developed that the ice was grounded on the bottom of the river and extended to a height of ten feet above the level of the water.... We used about twelve separate charges, each made up of 17 lb. of Gelamite No. 1, packed in 5-in. by 20-in. cartridges, to break this jam. These dynamite charges were placed as near to the base of the jam as possible. Some were fired as close as 8 ft. from the abutments of the spillways, and no apparent damage resulted. After the dam was cleared, the river was free of ice as far south as the city line. From this point to ... 3½ miles distant, the river was covered solidly with ice. Another ice jam had formed at this location and it extended from a distance of about 1½ miles up the river.

"Blasting operations began at the city line by placing two cartridges of 60% nitroglycerin dynamite, size 1¼-in. by 8-in., primed with a No. 6 electric blasting cap, on the surface of the ice near the middle of the river. When this charge was fired a hole was blasted through the ice. The river is about 400 ft. wide and about 25 ft. maximum depth at this location. A charge of two 17-lb. cartridges of Gelamite No. 1, each primed with a No. 6 electric blasting cap with 30-ft. duplex leg wires and connected in series, was lowered through the hole in the ice that had been blasted previously. The dynamite was placed as near the bottom of the river as the current would permit. When this second blast was fired it blew a hole in the ice about 60 ft. in diameter and, at the same time, displaced a large amount of water. This displacement created a raising and lowering action in the water in the river. This caused the surrounding ice to crack and to free itself from each bank, and permit the broken ice to flow downstream. Sometimes a charge of this size would free up to 500 ft. of ice from shore to shore. At other times we were less fortunate and had to blast again and again before any appreciable dislodgment of the ice could be accomplished. In some instances we placed the charges nearer the bank of the river; at other times we placed a charge on both sides. Blasting was continued in this manner until we reached a point about 100 ft. from the ice jam.... We fired the last blast there and it dislodged not only the remaining sheet ice, but also the jam which extended 1½ miles above it. The dynamite charge used was no heavier than those we had used previously.

"In firing all the blasts we used 3,983 lb. of Gelamite No. 1, 220 lb. of 60% nitroglycerin dynamite, 438 electric blasting caps of which 233 had 30-ft. duplex leg wires and 205 had 10-ft. leg wires....

> "Despite the fact that this unusual job with explosives had to be done on slippery ice, in very cold weather, it was completed without injury to the workmen or any damage to property."

Blasting, in order to prevent ice jams on the Raritan River in New Jersey, is described by Longstreet (1936).

> "... The most effective approach to the problem is a foresighted one, which on the basis of past experience, anticipates the course of events, and prepares accordingly.... This 'preventive medicine' consists, essentially, of blasting a line of weakness, if not a continuous open channel, in the ice along the river channel at each potential 'jam site'.... On this stream tidal cracks keep the river ice in a weakened condition along both shores. When a heavy thaw is expected ... danger points are blasted along the center of the stream. Then, when the ice begins to move, pressure from upstream shoves the ice floes down through these cuts, splitting the river ice apart. This creates a free channel. Some large sheets of river ice may be shoved aside onto low land; some may be broken by blasters working from the shore. But in any event, the river, which is the drain pipe for a thickly built-up industrial area, is kept open and functioning, and will not spill over.
>
> "... It appears that ice floes coming down the stream tend to crumble, but may be forced under the standing ice. Ordinarily, then, they ground on some underwater obstacle, and cause a jam. But where cuts have been blasted, they pop up in those openings, sometimes being crowded out of water by the pressure. The pressure of oncoming ice presently lifts a pressure ridge above and below the cut, and when this line breaks open floating ice wedges in, widening the channel, and the process continues to the next cut below.
>
> "This year, about the last of January, a survey showed that ice on the Raritan threatened particularly the city of New Brunswick....
>
> "Work began ... by blasting short channels where ice jams have occurred in past years.... (using) 40 per cent ammonia dynamite."
>
> "The charges were hung from sticks across the holes, so as to be about 18 in. below the bottom of the ice. Long experience has shown that, with ice not more than two feet thick, a wider cut is thus broken than otherwise. If the charge is too close to the ice, it breaks a small hole; if too deep, it may not break through.
>
> "The use of ammonia dynamite for this work calls for some comment, as it is not ordinarily recommended for wet work, and practically never for submarine blasting. The reason was that, should a charge be lost (actually, not one was during this entire job), a prolonged soaking in the river would be more likely to render it harmless to craft using the river, than if explosives of the more water-resistant gelatin type were used.... Besides 1,300 lb. of the ammonia dynamite, we had 100 lb. of

of 60 percent strength gelatin which was used where longer periods of immersion were necessary, and 100 lb. of 60 per cent strength L. F. Nitroglycerin Dynamite....

"... An opening 10 ft. to 15 ft. wide, and of a length depending on the number of holes, would be blown in the ice....

"Where particularly long cuts were needed, propagated blasts were very effective.... Holes were cut in the ice 4 ft. apart, and in each hole two cartridges (1¼ in. by 8 in.) of 60 per cent strength L. F. Nitroglycerin Dynamite were suspended from a cross stick.... Twenty-eight holes were thus prepared, and when the blast was fired by means of an electric blasting cap in one of the end charges, a cut 110 ft. long and averages 22 ft. wide was made. Previously 8-ft. intervals had been used for such propagated blasts, but at 4 ft. no trouble was experienced....

"Another useful method of preparing a propagated blast is to tie the charges on a line and pull them into position under the ice. First, a hole is cut at the upstream end of the desired line. Then another is cut 50 ft. to 100 ft. directly downstream from it. A sealed 5-gal. can is tied to a cord, put under the ice at the upper hole, and fished out at the lower hole. If the can is too buoyant, and will not move down with the current, it may be partly filled with water, so as not to bear up so tightly against the ice....

"If it is desired to break a large floe drifting by, a bundle of cartridges with lighted fuse is pushed out on the floe....

"A method of placing a charge under a jam or an ice floe at an otherwise inaccessible point is to float it down with the current. The charge is tied to a float, with a long enough cord so that when the float comes to rest against the edge of the ice the current will sweep the explosive underneath the ice to a point where it will be most effective. If desired, the float may be given less buoyancy, so that both float and explosive will be sucked under the ice...."

"We do not wait for the break-up to create dangerous situations, then hope to relieve them by spectacular bombing or blasting ventures. We study the river and its habits--seeking the danger spots ... then blast accordingly. Not too soon, for that would only waste explosives, but in time to prepare for the inevitable thaw and rise of the stream. We watch for pipe lines, cables, and other property that might be damaged. Bridges are usually looked on as probable jam sites. We blast under the ice whenever possible, for two reasons: it is more effective, and there is less noise to disturb people on shore.

"The central idea in all preliminary work is, not to create an open channel, but to make a line of weakness, and thus direct the tremendous force of the current and the floating ice toward cutting its own channel.... The rule, however, once the ice starts to move, is to keep it moving."

Campbell (1935) used dynamite to blast an ice jam at a railway bridge. Suspended just below an 8 foot thick ice cover, four 1¼ x 8 inch sticks of 40% dynamite broke the ice in 15 foot diameter holes. The ice was broken in a line parallel to the channel above the bridge without effect. Another channel was then cut below the bridge to pass the ice downstream when the jam was broken.

> "On February 13th the (lower) channel was blasted up to the bridge and a 150 ft. above it. The effect of breaking through the last barrier of ice was very quickly made apparent by the water and ice levels. In 24 hours the water level under the bridge dropped 3 ft. 3 in., and the ice level dropped 2 ft. 2 in."

Methods of using explosives to protect bridges from ice jams are given by Tavrizov (1964) and Rozov (1957).

Breaking up a heavy ice jam with dynamite on the Mohawk River is described by McNeil (1930).

> "Torrents of water pouring into the river from its tributaries loosened the ice and it started to move, but a jam formed a short distance from Schenectady and the state lands adjacent to the canalized Mohawk were soon flooded. The ice, extending in a solid mass as far as the eye could see, was packed 2 ft. above the lock walls, and held back more than 7 ft. of flood water....
>
> "Holes were bored through the ice with an auger and 1¼ in. by 8 in. cartridges of 60% ammonia dynamite were dropped in the holes and drawn up against the bottom of the ice. These holes were placed in 5½ ft. centers. In all, 2,400 cartridges of dynamite were used and 50 cartridges fired at a time."
>
> "Following the use of the explosives, the ice field broke up.... There was a channel of open water 15 ft. wide when the first piece became detached, and in an incredibly short time the field, extending for more than ½ mi., went thunderously down the stream, successfully negotiating the passage under bridges and the natural gorge at the Knolls. The flood waters immediately subsided and the river was at a normal stage within a few hours."

Williams and Williams, (1926) describe some "recent" advances in the use of explosives. Some similarity to current reports can be noticed.

> "Ice blasting should begin at the downstream end of the channel to be cleared so that the current may carry the loosened ice away. The best plan is to distribute charges under the ice for several hundred feet at the downstream end and to fire them all at one time....
>
> "The charge should be placed a sufficient distance below the ice to realize the full spreading effect of the blast. A charge of 10 lbs.

should be placed 2 or 3 feet below the surface. If placed just under the ice it will merely blow a hole through it at that point.

"Dynamite, if necessary, should be weighted in order to keep it from floating up close to the ice....

"The quantity of dynamite for each charge depends upon the thickness of the ice, the width of channel desired, and also upon the nearness of buildings bridges or piers. With ice two or three feet thick and holes thirty feet apart in rows sixty or seventy feet apart about eight to ten pounds of dynamite should be used in each charge.

"Although ice blasting in present practice is applicable only to comparatively short stretches and in connection with ice jams, it is described here to indicate what progress has been made in its use."

Byrne (1925) describes early uses of dynamite in blasting ice jams and methods still employed today.

"The best kind of dynamite for ice blasting is gelatin, because it is not injured by water and because it is heavy enough to sink. The 30% or 40% strength of gelatin dynamite is usually strong enough. The next best kind is 40% or 50% straight nitroglycerin dynamite. However, it is generally necessary to use whatever explosive can be most quickly secured, as ice blasting is likely to be an emergency undertaking, and any kind of dynamite will do the work--provided enough of it is used.

"This necessity for considerable quantities of dynamite is the first thing for the prospective blaster of an ice jam to fix in his mind, for from 50 lbs. to 200 lbs. will be required to break up an ice jam. When the great ice gorge at Niagara Falls was blasted several years ago, twenty-seven hundred pounds of dynamite were fired in two charges. That was an extreme case, because the ice was 70' high."

"... The ice blaster ... should work on the downstream side of the jam, so that the current will carry away the loosened ice. The best plan is to distribute charges under the ice for several hundred feet below the jam, in addition to the charges directly under the jam itself, and to fire them simultaneously with electric blasting caps and a blasting machine."

"The quantity of dynamite for each charge depends upon the thickness of the ice, the width of channel desired, and also upon the nearness of buildings, bridges, or piers. Ice 2' or 3' thick, and holes 30' apart in rows 60' or 70' apart, probably will require 8 lbs. to 10 lbs. of dynamite in each hole.

"The charge should be placed a sufficient distance below the ice to secure the full spreading effect of the blast. A charge of 10 lbs. should be placed 2' or 3' below the surface. If placed just under the ice, the explosive will merely blow a hole through it at that point."

Another early article (Explosives Engineer, 1923) describes briefly the use of dynamite to remove ice jams on the New York State Barge Canal.

> "... There are two methods commonly used in blasting ice gorges. One is to tie the dynamite to blocks of wood which are lowered into the holes cut through the ice. The blocks are then allowed to float under the ice a little. A blast made in this manner has a tremendous heaving action. Another method which takes less time but requires more dynamite is to fire large mudcap shots on top of the ice. In this method the dynamites that are less water-resisting can be used satisfactorily. It is best adapted for breaking up moving floes of ice. The primed charges can be dropped on the floe from the down-stream side of a bridge, or from the shore. The most common mistake of the inexperienced blaster is to underload the charges."

The methods best suited for removing ice jams with dynamite are also described in another paper (Railway Maintenance Engineer, 1919).

> "It is well to begin at the downstream end, considerably below the probable location of the gorge, and work upstream some distance above it, depending on the width and size of the stream. The ice should be practically honeycombed or cracked up below and above the danger point, so that when the 'rush' comes it will give or move easily without jamming or causing damage....
>
> "... Holes should be about 30 ft. apart across the stream, and from 60 to 75 ft. between rows. It is advisable to shoot one row at a time at first, then the execution of the charge can be noted and it can be determined whether or not it is advisable to decrease the charge, or space the holes further apart. For the initial charges from five to ten 1¼ x 8 in. cartridges of 40 per cent dynamite should be tied into a bundle with a stout cord, and each bundle primed with an electric blasting cap. One bundle of dynamite should be dropped in each hole so that it will be suspended in the water under the ice--even two or three feet under the ice is best...."
>
> "The size of the charge per hole will depend entirely upon the thickness of the ice. If two or three feet thick, about six 1¼ x 8 in. cartridges, or three pounds should be used in each hole. If thicker than this, from 8 to 10 cartridges or more should be used. Be sure to get the holes through the ice, as much greater efficiency is obtained by exploding the dynamite in the water than in the ice itself.
>
> "If the gorge or jam has actually formed it is well to honeycomb the ice below the gorge, as above described. Then at about midchannel, or what appears to be the weakest point of the gorge, a heavy charge of dynamite should be placed, under the ice, if possible; often it may be necessary to fire two or three heavy charges at different points if the gorge is a large one.

"If it is impossible to get through the thick ice ... a small charge will enlarge the hole and probably break through and permit placing the heavier charge in the water under the ice....

"The size of the charge must be regulated also according to the location and proximity of structures that might possibly be damaged by the explosion. It would be inadvisable to blast too heavily near a bridge pier. If, however, nothing like this interferes it is well to use larger-sized charges. The tendency of most people in using dynamite for blasting ice is not to use enough....

"If the ice is floating, a gorge can often be prevented from forming at some lower point ... by throwing charges of dynamite onto the cakes from the shore...."

In another early report La Motte (1914) also describes some of the principles used in blasting today.

"There are two general methods of procedure--one is to break up the ice in place without attempting to move it, so that it will be moved away by the pressure of the water when it strikes it; the other is to break up and remove the whole body of ice, beginning at the downstream end and breaking up the mass of ice and pushing it into the current as fast as it is loosened from the main body....

"It is a waste of time and money to attempt to explode charges on the surface. It takes enormous charges of dynamite to break the ice in this way, and even then about all the explosive does is to punch holes in the ice. The proper method is to explode charges of dynamite in the water under the ice and, if possible, against the side. This lifts up the ice in a large radius, breaks and cracks it in all directions, and if done in a line of charges extending across the channel can start an immense quantity of ice at one operation.

"The method ... employed ... where the danger is not particularly imminent is to punch a line of holes across the channel on the down-river side about 20 ft. apart and 20 to 30 ft. back from the clear water.... The holes should be 4 or 5 in. in diameter at least for ice up to 3 ft. thick. For this thickness of ice seven cartridges of 60 per cent dynamite, tied securely in a bundle with an electric blasting cap firmly inserted in one of them, are let down through the hole and allowed to be taken by the current a foot or two and held by it against the under side of the ice....

"Thicker ice requires proportionately larger charges of dynamite, the amount necessary being determined by experiment. When the area of breakage extends from one hole to the other so as to shake it up and loosen it thoroughly, the charges are about right."

"One reason why dynamiting ice jams is frequently unsuccessful is that the operator has an idea that a small quantity of dynamite is infinitely powerful, or that there is no limit to the work that one cartridge of dynamite will do...."

According to Brochu (1958), dynamite explosions under decayed ice produced holes of 2-3 meter radius instead of the expected breaking effect. Ice clearing was effective, however, since ice from the upstream breakup passed unhindered.

The use of surface explosives on Russian river ice and ice jams is given by Livshits (1961). The first part of his paper describes operations in river ice only. Ice jams are treated in the last section.

"The sphere of destructive action of the explosions depends upon the position of the charge in relation to the surface of the ice. The explosion of a small charge placed on the surface or in a thickness of ice, causes relatively little destruction....

"At the time of lowering the charge into the water, the greatest depth ice that an explosion cannot throw out rises up and splits into large cakes.

"Explosion of a charge at too great a depth leads only toward a rise of water for the craters through which were passed the charges.

"For blasting the ice in general ammonite was used.... Toward mechanical and heat influence ammonite is poorly sensitive; when fired it burns quietly without explosion...."

"The charges are adapted from the following weight: small 1-2 Kg, average 3-7 Kg, and large 10-25 Kg.

"Small charges are generally used for exploding floating ice...."

"The charges for submarine explosions (from 3 Kg and larger) are sunk under the ice by poles with crossbars or ropes (fig. 32). The length of the pole or rope is 2.5-4M. Because of the light weight of the ammonite some covering, such as a fastened load or a stone of a weight of 2-3 Kg is necessary...."

"The organization of explosive works must include: assignment of responsible persons under this authority, formation of blasting brigades, securing the explosives, means of igniting, subordinate (subsidiary) materials, means of connection, production of the charges, security measures of safety, carrying out ice reconnaissance, manufacture of holes for preliminary loosening of the ice, blasting of ice, and struggling with ice jams."

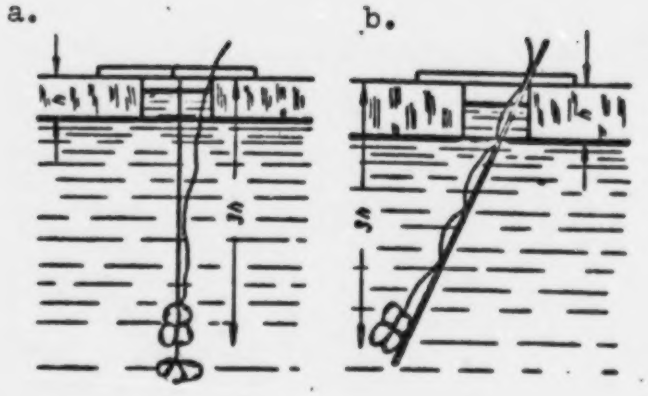


Figure 32. Methods of lowering charges for underwater explosions
a. from a crossbar; b. by a rope.
(Livshits, 1961)

"It is recommended that the explosion of ice be started when cracks begin to appear. These cracks appear as a signal of a possible rise in the river water, and consequently, the ice drift.

"The charges are lowered under the ice through ice-holes to a depth H, some distance from one another, equal to 3 + 10H on a rope or pole (fig. 32)....

"Calculations given for explosions of ice are put in Table 9....

"The distance between charges depends basically on the depth to which they are lowered and the goal of the explosions. If it is necessary to form holes, basically free of ice, the distance taken will be equal to 5 times the depths of immersion. For cracking of the ice cover a distance can be increased to 10 depths of immersion and more.

"As pointed out in the Table, the magnitude of the charge in all cases, when this is possible, must be specified by trial explosions, and also in the process of executing the work. If the depth of the river at the point of lowering the charge is less than the calculated size of immersion, the charge should be lowered into the water 0.5 M above the bottom.

"If below bridges or dams the ice drift rises opening the water surface, the upper ice field needs to be blasted near the shores, and also, if it is necessary, to break the ice field at points.

"In the absence of an opening in the surface of the lower pool it is necessary to create holes (Fig. 33). Maps of firm ice areas must be made before making craters for the lowering of the submarine charges. With riding side walls craters must be sheer.

"The craters are arranged in a chess board pattern. Explosives are layed out in a line. The charges in the craters are lowered only in front of the explosives of a given line; the explosives to be placed should not be nearer than 15M to the dam or bridge."

"After making the holes or freeing ice from important sections of the river below the bridge (dam), the ice should be blasted above the bridge (dam) in order to break up the ice field so that it would not make dangerous pressures on the supports.

"Against these supports, up current are formed a line of parallel clear channels. These lines across 10-15M, cut through craters and they explode the submarine charges in them....

"Training holes

"In the case where the impact of large ice blocks on the supports is dangerous, it is necessary to clear from ice all of the river surface above the dam to an extent of 200-300M, blasting the ice while, at the same time, making holes.

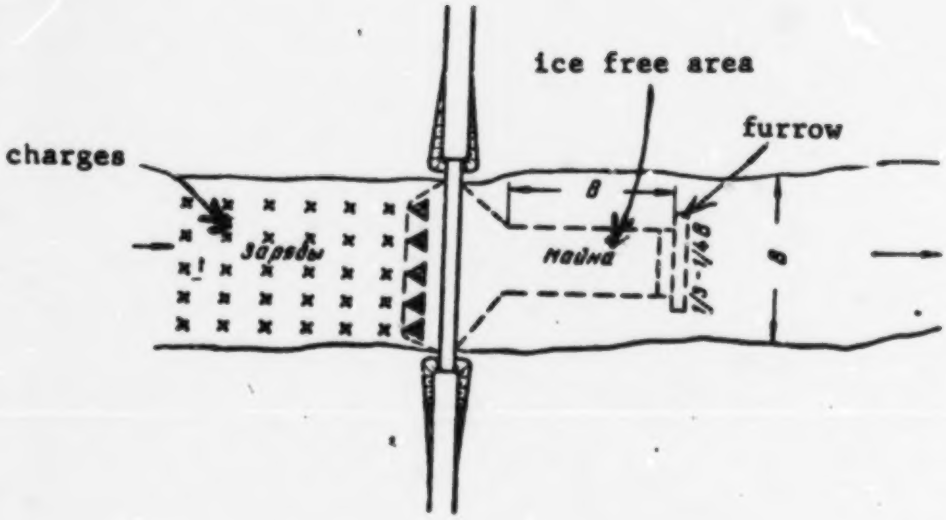

charges
ice free area
furrow
Заряды
Майна
B
B
1/3-1/4 B

Figure 33. Preparation of an ice-free area.

(Livshits, 1961)

"Holes are blown in the ice passage between the supports....

"During quiet ice drift the work of the barges is to direct the ice into the passage and prevent its piling up. During intensive ice drift it is necessary that they actively struggle with the ice.

"It is necessary to continuously receive information on the drift from upstream, and that of the lower stream of the river, and to watch the condition of the river above the construction. At the time of the appearance of large ice floes a size larger than the size of the passage in the dam or bridge, they must be broken into small pieces 1.5-2 Km from the construction, lessening the possibility of using submarine explosions through the craters.

"In case the possibility of breaking the ice field is not offered at a remote distance, it should be done at a close distance (about 0.5 Km) from the bridge or dam....

"The relation of the load of the charge to the ice thickness follows:

Ice thickness in M -	0.5	0.75	1.0,
Weight of charge in Kg -	2.0	2.5	3.0.

"The charges should be placed 20-30 M apart. In exceptional cases, if danger arises to the integrity of the bridge or dam, the explosion of a charge not greater than 3 Kg at a distance of not more than 10 M from the construction is permissible....

"Reduction of the size of the individual ice floes is made so that the force of impact and the static pressure on the construction will be reduced at the time of important ice stress in the area, so as to avoid an ice jam in the passages of the construction. When the area of ice subject to passage is small, all the ice is broken into pieces. Important areas of the ice cover are broken up only in front of the construction (generally not more than 1 Km). Sometimes it serves to break up the distant ice."

"Wrestling with ice jams

"At the time of liquidation of ice jams, when the ice chokes up nearly all the living sections of the river, and weak jams formed from small individual ice fields, it is necessary to distinguish powerful jams.

"Jams, formed at the expense of ice resting against bridge supports or ice cutters, must be liquidated rather quickly while they are weak.

"In that case, when it is impossible to get the ice off or to move, one should try to blow it up with small charges thrown from the bridge, shore, or a boat.

"Separated by the explosion, the ice passes into the current. At the necessary time the charge is lowered to the surface of the ice cover and ignited to form holes.

"Blasting of jams must be done immediately, so as to eliminate the impossibility of blowing up separate ice floes thrown onto it by the charges. The jam is blasted against the passage and the arrangement of the current in the open channel, in order to form a canal in the jam itself."

"Small-river jams are liquidated by explosion of charges, arranged in the middle of the river a distance from one another of about 10 times the depth (of the charge)....

"Techniques of liquidation of mighty jams amount to gradually splitting it from the inside. Explosives fill areas of the live section of the river, which are least choked up by ice, where the ice is mostly separated from the bottom.

"If the lower part of the jam is found to have an ice field hindering the emergence of the ice.... In narrow rivers the ice fields are split along their entire width.

"The liquidation of mighty jams is better carried by the simultaneous firing of a number of charges, placed in the cracks and holes between ice blocks or in shafts.

"For calculating the weight of the charge, the relationships in Table 10 must be followed.

"Ice jams on confluent rivers sometimes also contain a number of frozen logs, which increase the durability of the jam. For liquidation of such jams explosive charges of a greater weight or reduced spacing between charges are necessary.

"The liquidation of mighty jams can be accomplished after careful study of the situation. At the time of execution of the explosive work it should always be remembered that the breach in the jam can be sudden, therefore, it necessitates attentive observation of the movable ice, to maintain the precautions by walking on it.

"Great importance is placed on timely carrying out the measures against the ice jam; in the initial stages of formation of mighty jams in average and large rivers, when the length of it does not exceed the width of the river, the liquidation of the jam does not present any particular difficulty.

"In this stage the jam again is weak and consists of separate ice floes or several smaller ice cakes, supported by the edges of the shore.

TABLE 9.

Ice Thickness in M	Weight of Charge		Depth of Charge Immersion in M	Spacing Between Charges & Charge Rows in M	Length of pole or string for placing charges in M
	Toluene	Ammonite			
0,3	0,3	0,35	0,75	3,0	1,25
0,4	0,7	0,85	1,00	4,00	1,50
0,5	1,3	1,60	1,25	5,0	1,75
0,6	2,2	2,80	1,50	6,0	2,00
0,7	3,6	4,50	1,75	7,0	2,25
0,8	5,5	6,80	2,00	8,0	2,50
1,0	10,0	13,20	2,50	10,0	3,00

Notice: Accepted depth of charge immersion from the upper ice surface.
(Livshits, 1961)

TABLE 10.

Depth of Charge Immersion (H) in M	Charge in Weight in Kg	
	By a mass of explosion and charge spacing of 5H	By explosion of single charges and a charge spacing of 10H
1,5	3	15
2	8	40
2,5	15	80
3	25	130
3,5	40	200

(Livshits, 1961)

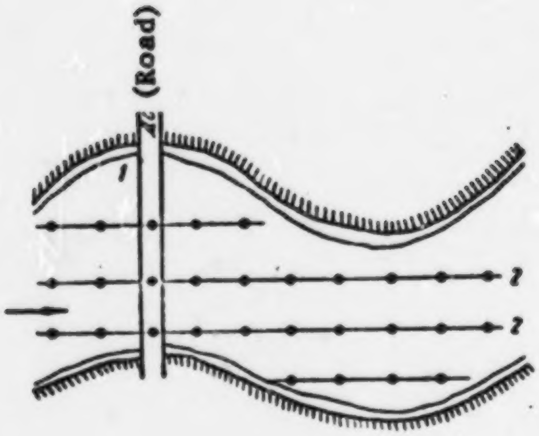


Figure 34. Scheme of explosives of the ice cover along the longitudinal trace. (Livshits, 1961)

"Northern rivers with a current from the South, break up at the source.

"Therefore, the ice starts moving toward the mouth and encounters a solid ice cover toward the lower sections, which is destroyed in principle under the influence of a flood wave. Thick mighty ice floe jams are formed locally provoking a rapid rise in water levels. It is observed that ice jams generally formed in spots where there is sharp turning of the river. Owing to the ice jam point, all spring flow is turned through secondary channels with very great current velocity. At the start of the ice drift special explosive works are conducted for the destruction of the ice cover, generally in places where the formation of a jam is assumed. This weakens the harmful activity of the spring ice drift, but does not completely eliminate the possibility of the formation of a jam.

"This method has great importance--the carrying out of preventive explosive work. An example of this would be the experiments of the Northern basin, when at an assumed ice jam point the solid ice was broken up in 1941, 10 Km^2 of the ice cover was worked on. Ammonite charges weighing 2.5-3.0 Kg were arranged in a chess-board pattern at a distance of 25M across the channel and at a distance of 40-50M along the channel (Fig. 34)....

"Such explosions weakened the ice cover, but did not create conditions for unhindered passing of the ice. An ice jam nevertheless arose, and for its liquidation 10-15 days were necessary, as well as a large additional quantity of explosive material."

Bezuglov (1959) describes blasting operations on the Neman River.

"... Explosives were used and manual exploitations of the ice were made before breakdown in order to weaken the durability of the ice cover; explosives were also used for liquidation of already formed jams. Explosive activity was started 5-7 days following the initiation of spring warm-up and was continued on the jammed stretches in the form of systematic channels installed in the jam down along the waterway of the river.

"Undermining of the ice was accomplished by ammonal charges of 5-7 kg ... lowered on weights to depths of 1.2 - 1.5 m. Blasting of the indicated charges demolished the ice in a radius of 3-10m. About 35-45 charges were exploded simultaneously. The average discharge of explosive substances on $1m^2$ of ice surface with thickness of 50-60 m. amounted to 0.027 - 0.030 kg."

Hinz (1930) describes how explosives were used on the Elbe River to protect waterfront structures from heavy ice accumulations. Clearing ice from a slip as described in the following report could have application for blasting close to structures.

"As planned, the shots made cracks in the ice over the rails. These were enlarged towards the ice coast, so that the ebbing tide carried the ice pieces into the river and allowed an easy cleaning up job.

"The 12 to 15 charges necessary for freeing one track were connected immediately after allocating each to one firing group. The final groups were fired at high tide, which covered the charge 4 1/2 ft. to 6 1/2 ft. and formed an excellent tamping. The effect of all these groups of shots was good. The charges detonated partly in horizontal and partly in vertical cracks of the ice, loosened on the connection of the ice and also cracked the 'ground ice' grown around the rails so that it could be loosened easily and allowed to drift away with high tide. The way of operation just described was used in ice from 12 ft. to 3 ft. thick after trials had disclosed that it was the most favorable and economical one. No drilling was done.

"For the ice cover less than 3 ft. thick, holes from 1 ft. to 2 ft. deep were knocked in with heavy pickaxes, as deep as possible and charged with .1 lb. to .2 lb. of explosives. The weak charge was tamped with glass sand, since no other material, such as sand or clay, was available. These charges also did their work as desired. Water failed as tamping in these short boreholes....

"Ammonia gelatin 1, which was used for blasting was found the most favorable and effective explosive....

Ice jam removal is described in the Explosives Engineer (1930).

"The Rhine had stopped its current at several places and all tributaries were almost entirely frozen. A change in weather with rain could cause immeasurable damage if all the ice were to start flowing. Therefore, every possible obstacle, which could stop the smooth flow had to be removed on account of the large amounts of ice to be expected.

"Blasting operations on the Rhine

"Blasting near Unkel

"On the right bank of the Rhine there was a solid ice layer, 1.2 m. long, 100 to 180 m. wide, and 0.80 to 4.00 m. thick, which surrounded Unkel in a curve. At the left bank there was an open channel about 70 m. wide.

"On February 22 test shots of black powder and ammonite 5, fired about 25 to 50 m. from the shore, did not have the expected effect. Single shots of 4 and 5 cartridges of ammonite 5, placed in hacked-out ice holes about 25 cm. deep, broke the ice layer but failed to loosen large ice cakes. On February 25 and 26 the holes were arranged crossways to the river bed in rows of 7 to 15 shots from 5 to 10 m. apart.

These rows were prepared about every 50 m. along the bank. Charges of about 10 cartridges of ammonite 5 and one priming cartridge of ammonia gelatin were fired in holes 30 cm. deep, covered with half a bucket of sand. The shots broke the ice layer and formed holes 3 to 5 m. in diameter. The surrounding ice layer was broken in long cracks, partly radially.

"To re-enforce the effect, compact charges of 1 to 2 cartons of ammonite 5 with a priming charge of 1 to 2 cartridges of ammonia gelatin were pushed under the ice in the holes nearest the shore ice. These shots tore part of the front ice edge completely.

"On February 26, ice from the Moselle carried along torn-off shore ice cakes of the Rhine 400 to 500 m. long and up to 120 m. wide. The blasts had widened the water channel and destroyed the still standing ice layer so much that no jam was formed. At Unkel, the shore ice was pulled along by the ice flow of the Moselle. The blasting method used was successful.

"Blasting near the Lorelei

"Another especially dangerous spot was near the famous Lorelei rock. From about 2 km. above St. Goar the Rhine was frozen fast, with but few interruptions, to Mannheim. It was planned to loosen the ice at the Lorelei rock and open the way for floating ice, thus avoiding an ice jam. For this purpose it was planned to blast the local ice masses up to an open water channel about 2 km. above the Lorelei.

"The upper ice layer was from 0.40 to 1 m. thick. Below was a pack ice layer 1 to 6.5 m., and at some places, even 25 m. thick. For the removal of the extremely thick and hard ice masses especially strong charges had to be chosen.

"On February 24 and 25, holes were hacked vertical to the direction of the river over the whole width of the river through the upper ice layer. Compact charges of 20 kg. of dynamite 1 were wound around 3 to 4 m. sticks and provided with 1 or 2 priming cartridges. The sticks were pushed into the holes between the upper and lower ice layer, and from 10 to 15 were fired simultaneously with an electric submarine blasting cap. The shots loosened considerable ice masses into numerous large single cakes of several hundred square meters, which floated slowly down the river. To hasten the work a government boat pushed after the broken ice, but this was found unprofitable.

"Future blasting operations, confined only at the place of strongest current in a sufficiently wide channel, enabled faster progress with a channel only 70 m. wide. The charges chosen may appear rather high on first glance but smaller charges, tried by government order, were without effect. The blasting work near the Lorelei, which served merely as a local protection, was also successful.

"Blasting at the Lower Rhine

"The Rhine from Orsoy to the Dutch frontier and beyond that up to the district of low and high tide, was one rigid ice surface. In Emmerich it was attempted to free ships by blasting, while in Orsoy blasting was restricted to shots for the protection of the local dike.

"The compact charges consisted of 2 1/2 to 5 kg. of mostly ammonia gelatin. Through the holes hacked in the ice these charges were put under the ice layer on wires and attached to wooden sticks. The shots, fired by guttapercha fuse, destroyed the ice.

"On March 4, after a blast near Wesel, an ice surface of several thousand sq. m. started to move and freed the Rhine of ice over a distance of 500 to 800 m. The floating ice cakes were piled up meter-high on the shores and were reduced by blasts made by crews in small boats.

"On March 8, a larger test blasting was made near Mehrum close to Wesel, before representatives of the government, the result of which was to serve as a basis for further blasting operations. The engineer, who supervised the blasting work on the Lorelei was also in charge of these operations. The ice was here 4 to 4 1/2 m. thick. Twenty-one holes about 2 m. deep were prepared, arranged in a circle 40 to 50 m. in diameter. The compact charges of 20 kg. dynamite were attached to wooden sticks, as when blasting near the Lorelei. The charge, weighing about 350 kg., was fired electrically with good effect.

"On March 8, the ice of the Lower Rhine started to move and floated away, so further blasting was not necessary.

"Blasting operations on the Moselle

"The Moselle was frozen fast from its mouth up to Trier, the ice having an average thickness of 70 cm. Blasting operations were started along the whole length of the river at different places on February 25, 1929.

"After the bridge pillars had been freed, series of about 10 shots were fired across the river bed. Also in this case the single series of shots was arranged parallel, at intervals of about 50 m. After charges of 3 to 4 cartridges were found too weak, 10 to 12 cartridges were used and good results were obtained. Some of the shots were fired electrically with submarine blasting caps, but most of them with gutta-percha fuse.

"The intended systematic main blast could not come to its full effect. A jam formed above Trier broke on February 25 at noon with a rise of the river of about 2 m., the ice sheet being about 50 to 60 m. thick. With the progress of the flood wave, the ice sheet was broken without great difficulty up to Coblenz.

"It was now only necessary to destroy the flowing ice near endangered bridges by throwing on it compact charges of 10 to 12 cartridges mostly ammonite 5, partly also ammonia gelatin. The effect differed. At some places the ice was destroyed, while at other places the action of the charges lying freely on the surface was very weak. It is believed that in these cases the charges chosen were too small.

"Blasting operations on the Lahn

"With short interruptions the Lahn was frozen fast from Niederlahnstein to beyond Giessen. The ice had an average thickness of 40 to 60 cm., and at some places up to 1.50 m. First the dams, locks, and stowage locks were freed.

"Series of so-called 'preliminary shots', consisting of an ammonite 5 or ammonia gelatin cartridge, arranged at intervals of about 50 m. across the river, and placed in holes about 20 cm. deep and covered, made holes about 1.50 to 2 m. in diameter. Compact charges of 5 to 8 cartridges, which were attached to pieces of cord about 1 m. long, were put into the water and rapid progress was made. A group of about 50 men blasted up to 4 km. of ice surface every working day. The shots were fired merely with fuse.

"Below Limburg very good results were obtained with ammonite 5 under water, even without special precautions for waterproofing the compact charges. The compact charges were exposed to the water not over 2 minutes. A few chloratite shots gave misfires in spite of special waterproofing. Above Limburg, ammonia gelatin charges were also used with good results."

"Blasting operations on the Neckar

"Blasting near Heidelberg

"The river was frozen to a depth of 45 to 75 cm. The main river bed at some places was filled with ice masses. Therefore the water flowing off had to displace the river bed at several spots. Six km. below Heidelberg to 3 km. above Mannheim the old river bed was free from ice. However, the ice could not be forced in this direction until the ships lying before the harbor of Mannheim were brought in.

"Outlet channels 30 to 40 m. wide were made along the river to about 300 m. above the Heidelberg dam, and below the bridges and dams. The ice was reduced by blasting with ammonia gelatin 1 fired by electric submarine blasting caps with wires 3 m. long. Holes were broken into the ice at 7 pace intervals in rows 10 paces apart and loaded with 0.5 to 1.2 kg. charges. Holes were placed in regular rows. Under the bridges and dams and 30 m. above and below the same, the holes were placed at intervals of 4 to 5 paces and distances of 6 to 7 paces and loaded according to the thickness of the ice with 0.3 to 0.5 kg. in the way prescribed.

"Although it was possible to reduce the ice, it could not yet flow off. Where the ice reached the bottom the holes were driven to the bottom if possible, at least until looser layers were reached. Charges of 1.2 to 2.5 kg were placed in rows at intervals of 4 to 6 paces. Because some buildings were only 50 to 70 m. away, many shots and small charges had to be used.

"To avoid premature flowing of the ice blasted up the river, an ice cover had to remain. Thus, it was possible to free the river bed almost completely up to about 400 m. above the Friedrichsbrucke. On the ice flow March 10, the first flood lifted the blasted channels from the Karl Theodor-Brucke to above the Heidelberg dam and forced it to flow off. As soon as the blasted channels became free, the heavy ice sheets lying in between also flowed away. In this way the river bed was freed from ice from the Karl Theodor-Brucke to about 300 m. above the Heidelberg dam, so that when the ice flow started the next day only one stretch of about 800 m. from the Karl Theodor-Brucke downwards was left a solid ice layer. This was blasted and loosened when the first water came through.

"Huge ice masses jammed about 3 km. above the Heidelberg dam pushed along towers of ice 2 to 3 m. high. At the ice-free water above the Heidelberg dam, it tumbled down and passed the dam and the following bridge without causing any damage. The ice sheet was no longer an obstacle; it passed cities and bridges without danger. Although we cannot claim with certainty that blasting alone secured the unhindered passage of the ice, these preventive arrangements surely contributed a great deal to it.

"Explosive

"Black powder

"Black powder in water proof containers, such as bottles, tin cans, and thin pipes, showed good pushing and reducing action at an ice thickness up to 50 cm. The preparation and water proofing of the single charges requires relatively much time and is out of question in blasting operations which have to be hurried.

"Shots with black powder on the Rhine near Neuendorf (north of Coblenz) are said to have been without effect. On the Lahn water proofed black powder charges gave good results with an ice sheet about 40 cm thick. Black powder placed in specially waterproofed bottles was not strong enough for loosening such strong ice masses near the Lorelei.

"Ammonite

"When ice sheets 0.50 to about 2 m. thick are blasted, ammonite 1 in compact charges of 5 to 6 cartridges (500-600 g.) up to 1 to 2 cartons (2 1/2 to 5 kg.) was used with very good results. For submarine blasting it is advisable to use ammonia gelatin as a primer, but ammonite charges should not be exposed to the water more than 5 minutes.

"Ammonia gelatin and dynamite

"If ice layers over 2 to 5 m. thick have to be blasted, ammonia gelatin or low-freezing dynamite is used, especially where a strong lower layer of pack ice is present. Compact single charges up to about 20 kg. and shots in series up to about 400 kg. have very good effects. In the case of shots in series it is best to use electric blasting caps for mutual support of the single shots."

"Blasting on the ice

"Blasting holes are made with ice axes, launching irons or brisant explosives. With the ice axe a groove 10 to 15 cm. deep is cut and the charges are put in to the holes. Tamping of the charge with snow or sand increases the effect. Usually 200 g. of ammonia gelatin 1 is sufficient for ice 30 to 40 cm. thick. The distance between rows and holes is usually 10 to 15 m. The size of the charges and the depth under the ice sheet are determined by test shots. In general, charges of 0.5 kg. are sufficient for ice up to 30 cm. thick, and 1 kg. charges for ice 30 to 40 cm. When black powder is used, three times this amount is necessary. Introduction of the charges under the ice cover is done best with a wooden rod.

"Removal of ice jams

"If ice jams have to be removed first, make sufficient outlet for the water (preliminary flood). A disturbance of the equilibrium of the ice masses piled above and below one another by blasting can break the jam for great distances and move the masses. Since the breaking down occurs only some time after blasting, entering an ice jam the removal of which has been started, is always dangerous. Endangered workmen should be provided with safety belts.

"Boards should be used for walking over the ice. In cases of emergency these can be held by ropes. When the piled up ice cakes allow it, men can approach the jam in a flatboat and put charges in or under the ice. Gas or water pipe can be used in pushing the charge between cakes.

"When the ice is frozen to the bottom, it is best to prepare two rows of holes ending about 10 or 15 cm. above the bottom, and to load them with large charges. Then when a flood comes the water is able to flow much more easily through the ice and to drag along the fragments formed.

"Ice jams in narrow waters can be removed also by bundled charges with well fastened fuses thrown on the ice from the bank.... If cartridge bundles are thrown on floating ice cakes from the shore or from a bridge, bind a piece of wood to the bundled charge to prevent it from rolling off the ice cake."

"The amount of explosive to be used depends upon the thickness and formation of the ice cover and the local conditions. In the case of unusually thick ice masses as near the Lorelei and the Lower Rhine, charges of the chosen strength were absolutely justified. The ice flow setting later, which in spite of the huge ice masses took place everywhere without blocking, has confirmed the correctness of the precautions of the authorities.

"In smaller rivers, appearing less dangerous, blasting operations have not been carried out. However, this omission was found very dangerous when the ice flow set in. For example, on the relatively small Wied the ice flow caused great jams at the bridges in a short time, which had not been freed from ice, and destroyed them entirely or damaged them greatly at many places."

A recent report (Antonov, Ivanov, and Nolimov, 1964), recommends explosives for clearing ice jams. "One effective method for struggling with these ice jam phenomena is carrying out timely explosive work on the ice bar footings working in a downstream direction."

Waas (1963) recommends ice breakers as opposed to explosives on the Rhine River. "Other ways, such as explosives, have usually little actual importance, but they can occasionally be useful psychologically when the icebreakers fail."

Siegfried (1957) also prefers means other than explosives to control river ice. "Explosives are not used to break the ice cover on the canals. Artificial raising and lowering of the water levels in the canals is much more effective than explosives for breaking the ice cover."

On waterways having a current, "explosives are rarely used for destroying ice cover. Explosives should only be used in exceptional cases, depending on the reasons for the use and the locality in which they are used. Explosives were used to clear an ice jam in the winter of 1879-1880 near the town of Saumur on the Loire River. This was done to prevent a catastrophy similar to that which occurred in 1789 near Orleans. The charges used consisted of black powder and dynamite. The use of explosives will endanger constructions along the river bank and presents the possibility of destroying fish in the river."

He further reports that in fluvial marine estuaries, explosives are sometimes used to assist ice plows.

Without stating operational details, Karolyi (1963) describes a 50 meter wide channel blasted through on ice jam on the Hungarian Danube in 1963.

Zivkovic and Ivanovic (1954) describe blasting operations on the Danube during one season. Effective placement of charges as a function of ice structure is given.

The effective use of icebreakers on the Netherlands waterways is described by Wemelsfelder (1957). Explosives are not recommended.

> "In such cases explosives are employed; yet the results don't come up to expectations. By the blast the ice is thrown up into the air and a crater is formed. But if the charge is placed a few meters from the ice border, parts of the ice dam may fly off in a downstream direction. So removal of ice dams by means of explosives goes on very slowly."

Bock (1957) favors the use of icebreakers for removing ice jams on the Elbe, Oder and Vistula.

> "During the ice fighting, blasting was only used in very few special cases. The results were not satisfactory. It was undertaken after the ice breakers became ice bound, but owing to lack of removal results were disappointing. The charges (up to 25 kg) were mounted underneath the ice cover. Larger blasting areas did not prove advisable, as the broken blocks, due to lack of removal, piled up and reinforced the ice cover by fresh freezing."

Ice jam blasting is not recommended by Kravchenko (1959). With jams 100 km long on the Dniestr River only 0.5 km per day could be cleared with explosives.

Liser (1959) mentions the use of explosives in the Yenisey River.

> "Annually, explosives are utilized, just before breakup, to promote activity in the centers of possible ice jams. These have a marked influence on the breakup process, and in some cases, were successful in preventing the formation of ice jams altogether."

In their study in Danube River ice conditions between the Morava River and the Black Sea, Horvath and Laszloffy (1957) state that explosives are used to break up the ice. No details of techniques or results are given. In describing the use of explosives in Hungary they state that the "methods were applied several times, but none proved satisfactory, they were applied more for their moral effect. Either explosives or the assignment of icebreakers is applied, but there remains the difficulty that ice blocks that may be detached by the intervention cannot drift down freely but stick together."

In an earlier paper Laszloffy (1948) discusses the use of explosives as one means to continually impede freezing.

The following procedure was used: "Because of the tide, only 3 to 5 hours daily could be utilized for placing the explosives charges. At the lowest water level, charges of .4 lb. to .6 lb. (2 to 3 cartridges tied together) were put into cracks which lay dry during low tide. These were placed at a depth of 3 ft. to 4 1/2 ft. in such a way that the rails could not be damaged by the explosion, the distance being about 3 ft. away from them. When the charge had been placed properly, it was pinched tightly so that the rising tide could not disturb its position."

"... The effect of explosives is appreciably reduced by the phenomenon of re-freezing. On the basis of experience gained in the course of half a century ... it is impossible to clear the long reaches of the river of ice by means of explosives, although they sometimes render good service, chiefly local. The natural forces that manifest themselves at the time of the setting in motion of the ice are so powerful ... that by comparison the effect of explosives amounts to nothing."

According to Zakharov and Chizhov (1956) blasting operations during one spring on the Syr Darya and Amu Darya Rivers caused ice jams downstream. They feel that blasting should be used only in unusual cases.

Keefer (1898) describes an early blasting attempt on the St. Lawrence River. It is interesting that a lack of success is attributed to frazil accumulations.

"An experiment was made in March, 1887, in view of a threatened flood in order to ascertain the possibility of loosening an ice blockade by means of explosives. Eight hundred holes were made and over two tons of explosives (chiefly dualine) were fired about ten feet below the surface. The experiment ... was a failure, chiefly, as it is believed, in consequence of the great depth of frazil under the surface, cushioning and preventing the transmission of a blow to the surface ice."

Thermite

Thermite, a mixture of iron oxide and aluminum powder, is a heat producing incendiary. The major use of thermite to break ice jams in North America was by the controversial Dr. Howard T. Barnes of McGill University. Some use of thermite in ice jam removal was also attempted in Russia (Laktionoff, 1957).

Barnes (1926) describes an ice jam on the Allegheny River: "The constriction of the river at Brandon, 14 miles below Franklin caused the ice to stop and jam in such a way the entire mass above filled the gorge to that city....

"Towards the end of February a large quantity of ice came down from Kinzau, and quickly jammed into the pack which held below Franklin without dislodging or moving it. This caused the river to become packed from Franklin to Oil City, a distance of 8 miles, with a rapid rise of water level, higher than had ever been experienced by these communities.... This second run of ice blocked the river up to Oil City, and left a solid ice gorge for 20 miles. In a few days more ice came down and blocked for 5 miles above Oil City, making a solid and almost dry ice jam 25 miles in extent."

Continuing, he describes the use of thermite. "No attempt was made to treat the upper pack from Franklin to Oil City, because this was being weakened by the effect of the open water above Oil City at the head of the jam....

"The object of the first thermit treatment was not to dislodge the ice ... but to open channels under the surface. The water had to be brought down into the old pack and by its presence do two things; relieve the flood level above, and afford water enough to lift the lower ice and get it ready to be passed on down the river without gorging and causing more floods.

"With this in view, all work was concentrated on the heavy packs and the thermit containers fired as low down in the ice masses as possible. The liberation of this great heat had the effect of burning out great areas under the ice, and the force of the explosions, which resulted from the heated metal in contact with the ice and water, caused cracks and disruption which allowed the water to force its way through these places under a high head and gradually work its way down, clearing and melting a channel much larger than was evident to the eye at the time....

"All of the time up to March 18th was taken up with intellignet use of the thermit at the critical points....

"From the 10th to the 20th, when the weather turned very mild, the gorge was held in control in this way, and the whole pack was observed to move very slowly downward as the water was brought down....

"On the afternoon of the 20th, the upper pack began to move under the weakening action of the sun....

"On Monday, March 21st, two heavy charges of thermit were set off at the two points in the new jam at Reno where the pack was greatest, and these were effective in relieving the flood in Oil City, and were so gauged as to put the Reno bridge safely back on its piers without damage of any kind....

"On Tuesday, additional charges were inserted in the pack to bring the ice level down to a safe distance below the bridge, and then a concentrated attack was made on the gorge to remove it entirely....

"Under the terrific action of these thermit charges, the gorge was shaken loose in great patches and sent down the river safely, the lower pack giving just ahead of the upper, thus avoiding any flooding except for a short time at Indian Bend, where some of the track embankment was washed out. This was from the great rush of water from the upper pack meeting the resistance of the slowly-moving ice below. Very little damage was done, however, and by 6:30 o'clock in the evening the ice was all moving on down easily, and by late evening the river levels at both Oil City and Franklin were back to normal."

Barnes cites several complementary statements on the operations by local officials and members of the press. Opposing views were also offered: "Even after the gorge had gone out, the United States Army engineers at Pittsburgh sent out a bulletin to the effect that the ice had gone out under the pressure of high water, without giving any credit to the thermit operations."

Probably the least biased account of the thermite operations is given in an appendix of the report by B. L. Bannon who was in charge of placement and detonation.

"Wednesday, March 10th, 1926

"Shot No. 1.... The container was of the double-lined type. The thickness of the ice ... was 6 feet, and the depth of water was 10 to 12 feet.... The reaction was not as noticeable as in the case of the shots fired in the single-lined containers the day before. There were no flames shooting high into the air or the deep rumbling and rolling motion of the ice as noted by the single-lined container....

"Shot No. 2. The second charge was placed in 12 feet of water, and the thickness of ice was 8 feet with a quantity of slush ice underneath. This shot ... lasted for ... one minute, during this period there were two very pronounced reports. Water boiled up through the ice at a distance of 8 feet from the hole for a period of 10 minutes, and cracks radiated from the hole for a distance of 75 yards. The ice from shore to shore was shaken by a loud crumbling and rolling action. There seemed to be more of an equal distribution of energy....

"Shot No. 3.... The thickness of ice was 8 feet and the depth of water over 14 feet. This shot was placed at the edge of a pressure ridge between two large cracks in the ice. It also was successful, there being two very loud reports, (similar to those in the case of shot No. 2), and a few sheets of flame shot into the air to a height of 6 to 8 feet. Upon examining the hole after the shot was fired we found that it had been enlarged to 10 feet in diameter. Five minutes later the boiling action appeared very noticeable at the surface. The river at this point was about 500 feet wide and the ice shook considerably from shore to shore. This container was also lowered about 4-1/2 feet underneath the surface of the water.

"Shot No. 4.... The thickness of ice was 4 feet, and the depth of water in the channel over 14 feet. This container was lowered 5 feet under the surface of the water. There were three loud reports and one less distinct at 3 or 4-second intervals. Balls of fire shot out of the hole at each report, and upon examining the spot we found that the container sides were not destroyed, the top and bottom only being missing. There was no violent upheaval as noted before, and although the shot did some good it was not as satisfactory as the other three.

"Shot No. 5.... The thickness of ice was 5 feet and the depth of water over 12 feet. There was a pulsation of 3 inches at this spot and this appeared to be very violent at times. This was also a successful shot, heaving the ice up 6 inches accompanied by a violent boiling action about 25 or 30 feet down river from the hole, which lasted for ten minutes.

"Shot No. 6.... The thickness of ice was 6 feet and the depth of water over 12 feet. After the shot was fired a deep rolling motion took place and a series of short sharp reports, accompanied by a boiling action....

"Shot No. 7.... The thickness of ice was about 11 inches with a quantity of slush ice underneath, and the depth of the water over 12 feet. This shot was accompanied by two loud reports and a deep rumbling and rolling motion of the ice for a radius of 300 feet, while a boiling action was also noticed.

"Shot No. 8. This charge was a small double-lined container and was fired about 60 feet nearer the shore than shot No. 7.... It seemed to take longer for the reaction than in the case of the single-lined containers.

Ice shot up into the air to a height of 75 feet, and small sheets of flame were noticed above the hole.... There was also a slight rumbling and rolling motion of the ice but not as pronounced as in the other cases.

"Thursday, March 11th, 1926

"Shot No. 1. This charge was placed on the lower end of the ice jam.... This ice was projecting into the open water for perhaps 50 feet from the main pack. After the shot was fired there was a reaction lasting for fully one minute. Sheets of flame and black smoke rolled out of the hole and a series of low deep rumblings took place, then a loud report ... and ice and part of the container were thrown 200 feet into the air.... The hole ... had been enlarged 30 feet in diameter and huge cakes of ice, 18 to 24 inches, were all jumbled and tossed about. The ice at this point was 11 feet thick and resting on the river bed. A slight settling movement was noted five minutes after the shot was fired....

"Shot No. 3. This shot was placed at the edge of the main pack ... was of the special ice thermit. There was nothing unusual about this shot apart from the rumbling and short flames which shot out of the hole....

"Shot No. 4. Was placed 250 feet north of shot No. 3, with a charge of dynamite 50 feet away and both fired together. A section of ice 200 feet long was moved down stream.

"Monday, March 15th

"Shot No. 1.... It shook the ice for about 500 feet and fire shot into the air for about 25 feet. Two explosions occurred and water boiled for about five minutes. There was 18 inches of ice, and a single container was used.

"Shot No. 2.... The container came out of the hole and water boiled out for about five minutes. The thickness of the ice was about 2 feet.

"Shot No. 3.... There was a thickness of 2 feet of solid ice with slush ice underneath. This shot shook the ice off the bank along the shore, and shook the ice from shore to shore. There was not much of an explosion and not much change in the hole.

"Shot No. 4.... The thickness of the ice was 2 feet solid, with slush ice underneath. Fire came out of the hole to a height of about 25 feet, but there was not much change in hole.

"Shot No. 5.... There were 2-1/2 feet of solid ice with slush ice underneath. The shot shook the ice from shore to shore, with two explosions, and left a hole about 15 feet in diameter....

"Shot No. 6 was fired ... with 3 feet of solid ice and slush ice underneath. This shook the ice from shore to shore, boiled at the hole for about five minutes, but did not make much change in the hole....

"Shot No. 7 was fired ... where there was solid ice 18 inches thick, with slush ice underneath. This shot shook the ice from shore to shore; fire came out of the hole to a height of about 5 feet, but did not make much change in hole....

"Shot No. 8.... It shook the ice for about 200 feet, but not much fire came out of the hole. There was solid ice about 12 inches thick with slush underneath. There was not much change in the hole....

"Shot No. 9 ... did not result in much of an explosion, although water boiled at hole for about five minutes, without much change in the hole....

"Thursday, March 18th

"Shot No. 1.... There was one deep report and a small quantity of black smoke. Water shot up around middle pier of bridge, covering the ice to a depth of three to four inches. It also gave the ice a good shaking. The ice was from 3 to 4 feet thick, with plenty of water.

"Shot No. 2.... There was one loud report and flames and molten metal were hurled high into the air. This shot also gave the ice a good shaking.

"Shot No. 3.... The ice was in layers of 18 to 24 inches in thickness to a depth of over 8 feet. There was a series of short sharp explosions, then one loud report. Water spurted out of the ice at a distance of 150 feet from where the shot was fired. It also tore a hole in the ice about 30 feet in diameter.

"Shot No. 4 was placed ... in layers of ice 18 to 24 inches thick, to a depth of over 8 feet. There were two reports and flame shot out of the hole to a height of 6 feet. It tore a hole 15 feet in diameter in the ice. There was also a small part of the container left."

Barnes (1926) comments on the use of thermite on the St. Lawrence River.

"Two charges of thermit were used last winter in the ice jam at Chimney Island below Ogdensburg which cleared out over a million tons of ice in nine hours, and left the south channel free and clear. The river levels were restored quickly. This jam was solid to the bottom at some points in 70 ft. of water."

In his book Ice Engineering (1928) Barnes also describes thermite operations. The descriptions are similar to the above statements. He makes the following comments on safety. "The reaction makes little or no noise and is admitted by experts to be the slowest explosion known. On account of this fact it can do no harm to concrete structures, or bridge piers in immediate contact with the reacting thermit, and no harm has ever been done to fish in rivers or lakes where it has been used.

"For ice control in thickly settled communities it offers no unpleasant or dangerous features. There are no detonating noises to break windows, and the thermit is itself absolutely non-explosive and safe to handle and transport...."

In describing experiments by Barnes, Ewens (1938) states, "Of the several methods which have been tried for removing impacted jams, the use of thermit has proven by far the most effective....

"... The thermit ... is placed in steel cylinders and ignited electrically. The heat produced by thermit reacted in this way is so intense that the mass of molten iron which carries the heat is too bright to look at without dark glasses. A temperature of from 2,500 deg. to 3,500 deg. C. is produced in a matter of a few seconds. While the actual number of heat units is small, the high temperature is very effective."

Ewens describes two types of ice jams and methods to combat them. In the first type the jam has sufficient water flowing under the packed ice to allow the following operations.

"In dealing with jams of the first type, it is necessary, as has been mentioned, to destroy the key point of the jam, and thermit is very effective for this purpose. A hole is cut through the surface ice and the thermit unit placed in the underhanging ice at the critical point. The reaction greatly enlarges the hole in the ice, and causes a wave through the entire field. Water seeps in through the holes made by the thermit unit and gradually washes its way along, undermining the pack and removing the underhanging ice."

"A second type is that known as the dry jam. In this case a large jam, often many miles in length, is packed together by ice shoves until a solid mass is formed right to the bottom of the stream, so that no water can flow past it. This type of jam closely resembles a glacier, and of course, results in very serious floods. Since there is no key-point, channels must be opened in the ice to allow water to flow through, eroding and washing away the ice. This is much more difficult than destroying the key point of the first type of jam, but if an open water channel can be maintained, dry jams should never occur."

"In jams of the second type, thermit is used in a similar way, but here the object is to burn and crack channels in the ice and weaken the surface, in order to start water flowing through and under the jam. The water, once it starts flowing, will break up and remove the jam. Each thermit unit acts as a point of infection which spreads over an increasing area until the water melts its way through and comes out the hole blown in the ice. It then cuts its way down through the pack."

Laktionoff (1957) describes the use of explosives to combat ice jams in the USSR.

> "The measures taken in combatting ice-jams though involving considerable technical difficulties are less complex than those resorted to in the case of ice dams...." ('a kind of a natural dam under the ice cover whose body consists principally of small crystals of bottom ice transfused with water').
>
> "The employment of varieties of blasting operations as well as of diverse preventive measures must be regarded as specially effective in dealing with these phenomena. When eliminating an ice-jam its center of pressure ('the lock') is to be correctly judged. With the center of pressure destroyed, an ice jam will disintegrate under the action of powerful hydrostatic pressure of a mass of water accumulated above this ice barrier.
>
> "Places at which ice-jams and ice-dams usually occur on rivers are nearly always the same.
>
> "By a number of small preliminary blasts effected at places arranged in the chess-board order or better still along some definitely chosen lines the ice covering is weakened and the ice passes the danger spots unobstructed."
>
> In favoring thermit over other explosives he continues: "With other explosives a larger part of energy is wasted in throwing ice up in the air whereby the effectiveness of the blast is weakened.... While blasting of various explosives is useful to some degree in doing away with ice-jams it does no more than leave a hole in the ice and further solidify the surrounding masses of ice crystals in case of an ice-dam."

A report on the removal of an ice jam at French Creek in Pennsylvania is reviewed in another section of the report (Thalimer and Burfoot, 1960). In a detailed operating report on the same ice jam (Pittsburgh District, Corps of Engineers, 1960), the disadvantages of thermite for clearing ice are given.

> "The use of thermit as described by Mr. Barnes in his book requires placement of charges of about 100 lbs. of thermit in special containers of considerable weight. The transportation of such heavy charges, due to the general inaccessibility of a large part of the Meadville ice jams, except by foot or air, would have been most difficult."

Surface explosives

ANFO

Bezuglov, A. A. (1959) Prichinyi i mechanism obrazovaniya ledyanyikh zatorov na r. Nemane, preduprezhdenie i bor'ba s nimi (Causes and mechanics of ice jam formation in the Neman River, its prevention and control), Trudy Vsesoyouznogo Gidrologicheskogo S"ezda, 3rd Congress, 1957, vol. 3, p. 406-414 (text in Russian). English translation by U. S. Lake Survey, Detroit 1967.

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Aerial explosives

This section presents summaries on aerial explosives (i.e. bombs, rockets, etc.) including conventional explosives dropped or placed from planes or helicopters. Aerial explosives have received considerably less attention than surface explosives. This is probably due partly to the added danger involved to nearby inhabitants and property. Opinions vary widely on the effectiveness of bombs to combat ice jams.

Williams (1953) describes bombing missions of the U. S. Air Force in Alaska.

> "Since 1943 the Air Force has patrolled the Yukon and Kuskokwim Rivers and their tributaries during spring break-up. The purpose of the patrol is to locate and bomb ice jams in an effort to break them before they cause flooding of villages and military installations. The patrols and bombing missions were initiated after the first of the disastrous floods at Galena Air Base in 1943; this and later floods focused attention on the problem of ice jams and river floods....
>
> "a. Galena Air Base.
>
> "Assistance was summoned during the 1943 flood at Galena Air Base, and the Air Force responded with bombers which dropped 34,400 pounds of explosives on an ice jam.... The bombs were 250-, 300-, and 500-pound types; some were fused to explode instantaneously and others to explode with 0.1 second delay (Hendry, 1943). Bombs dropped on the large pans merely made holes in the ice. Hendry (1943) reports that the ice jam broke after the last bombing run.
>
> "In 1944 Galena Air Base was flooded again by river water impounded by ice jams (Pewe, 1948).... Again, bombing operations were carried on by Air Force planes from May 17, several hours after formation of the ice jam, until noon May 19, when the jam broke.
>
> "After the floods of 1944, a dike designed to withstand floods 2 feet higher than the 1944 level was constructed around Galena Air Base. In late May, 1945, an ice jam formed at Bishop Rock and caused the river to rise rapidly. On the second day after break-up, the water level ... broke over the dike (Reed, 1945). The Air Force dropped thirty-three 500-pound bombs and forty-four 1,000-pound bombs with no apparent effect. On May 26 and on May 27, eighteen 1,000-pound bombs and four 4,000-pound bombs were dropped before the ice jam broke (Reed, 1945). In Reed's opinion bombing only put holes in the ice and did not have the shattering effect required to break the ice jam.

"b. Aniak.

"During the 1948 break-up flood of the Kuskowim (sic) River at Aniak, Air Force fighter-bombers were called on to break the ice jam causing the floods. Both rockets and 500-pound bombs with delayed detonation fuses were used, and flood level is reported (Univ. Minn., 1950) to have dropped immediately after completion of the mission.

"c. Bethel.

"During the May 1948 floods at Bethel on the Kuskokwim River, Air Force aircraft were assigned to bomb the ice jam causing the flood. The results were reported successful by one of the participating officers (Univ. Minn., 1950).

"d. Beaver.

"Bombing of Yukon River at Beaver in May 1949, was carried out by aircraft... According to local residents, there was no immediate flood danger and no ice jam. At the time of the bombing Fort Yukon was inundated by a local ice-jam flood. At Beaver, however, the river ice had not broken up at the time of the bombing, and the bombs merely made holes in the ice without breaking it up.

"e. Fort Yukon.

"In May 1949, the Yukon River at Fort Yukon was blocked by an ice jam at a sharp bend in the main channel downstream from the village. Water rose rapidly upstream from the ice jam and reached a peak of 2.5 feet above the record 1937 flood.... At the peak of the flood, water was about 6 feet deep in the main street. The ice pans moved through the village.... Aircraft were summoned to relieve flood conditions by bombing the ice jam and to drop relief supplies to the residents. Bombing continued for several days until the jam broke and flood waters receded. Opinion of the local residents was divided as to the value of the bombing.... During the 1949 break-up the Air Force expended 74 tons of 500-pound bombs (Jessen's Weekly, June 10, 1949); most of this tonnage was expended at Fort Yukon, and the balance at other villages along the Yukon and Kuskokwim Rivers.

"f. Saskatchewan River, Saskatchewan, Canada.

"A radio report, received during the winter of 1950-1951, indicated successful bombing of an ice jam on the Saskatchewan River with one 1,000-pound bomb by the Royal Canadian Air Force.

"g. Appraisal of bombing results.

"The results of ice-jam bombing missions by military aircraft have been inconclusive. Opinions of officers participating in the bombing missions and of observers on the ground are divided. Ice jam persist until sufficient water is impounded to raise the ice and float it downstream. Bombing missions are continued as long as the ice jam persists. Therefore, the apparently good results of some bombing missions may be misleading, because river level sometimes rises enough to float the jam within a few hours after the bombs are dropped."

A definite opinion on ice jam bombing is expressed by Henry (1965) in a paper on the ice jam floods of the Yukon river.

"When an ice jam has caused flooding of a village, attempts have been made to bomb the ice-jam. The U. S. Air Force has flown many sorties and dropped many tons of bombs.... Usually the bombings are of no avail, one reason being that the effective dam is hidden under several miles of ice and the bombs are not dropped on the dam. There is yet another factor. The Yukon is in the permafrost region and like all Arctic rivers freezes from the bottom up, as well as from the top down. This 'anchor ice' normally comes to the surface two or three weeks after the top ice goes out. It catapults to the surface in chunks 20 or more feet in diameter and four or five feet thick.... The bombing shakes the anchor ice loose, and thus adds more ice to the jam...."

Bombing runs on ice jams at McGrath and Galena, Alaska over a four day period are described in reports by Brady (1947).

He recommends: "That charts of river channels be procured if possible" because, "when rivers are frozen solid and are causing the water to back-up, bombing is best effected in the deep channels so that the ice can float away as it is broken. Without proper river channel charts there is no way of telling from the air where the channels are. Unless channels are bombed, any attempt to break-up the ice to relieve pressure appears to be futile.... Difficulties in finding the deep water channels were encountered on all missions."

A bombing procedure is also recommended.

"On frozen rivers with large sheets of ice, small bombs (250 lbs.) should be used in the channels. Bomb four to five hundred yards from the beginning of the ice jam and continue up river. If there is water trapped underneath the ice this will release the pressure and the water gushing through the bomb holes will tend to break up the ice.

"When broken ice has jammed and caused ice and water to back up behind it is recommended a relatively large bomb (500 lbs.) be used."

"Caution should be used in low level bombing of ice. Ice fragments are thrown much higher than ordinary bomb fragments. A five hundred pound bomb throws ice fragments from fifteen hundred to two thousand feet. It has been made S.O.P. for this organization that when bombing ice with instantaneous fuses that no ship will fly lower than three feet per pound of the largest bomb carried."

In a more recent report, Froehle (1966) adds an additional note of caution.

> "The Navy has attempted to knock out the ice jams by dropping 500-pound bombs from an altitude of 2,000 feet. The questionable accuracy of this method and the limited area in which this can be done without danger to villages and natural resources made this impractical."

The Rock Island District, Corps of Engineers (1967) summarizes the most recent bombing activities in Alaska.

> "a. 1962 Spring Breakup: Only one ice jam ... occurred which could be effectively removed by bombing. A bombing run of 16 bombs with 8 hits and 8 misses broke up the jam which had formed downstream from Tuluksak on the Kuskokwim River.
>
> "b. 1963 Spring Breakup: Three ice jams where bombing could be effective occurred during the spring breakup of 1963. Flooding at Bethel resulted from ice jams between Bethel and the mouth of the Johnson River. To relieve Bethel, a bombing run of 16 bombs with 8 hits and 8 misses was made on several small jams to open sloughs along the Kuskokwim to allow the water to flow through side channels. The second jam resulted from an ice floe grounding on a sand bar below Kwiguk on the Yukon River. A bombing run of 8 bombs with 4 hits, 3 misses and 1 dud broke up this ice floe which then moved downstream and formed against the solid ice of the Bering Sea at the mouth of the Yukon. At low tide, with a maximum head against the jam, a bombing run of 16 bombs with 12 hits and 4 misses successfully destroyed it.
>
> "c. 1964 Spring Breakup: Several ice jams on the Kuskokwim River occurred, three of which could be removed by bombing. A small ice jam directly downstream of Aniak, a large jam at Devil's Elbow and a large jam at Aniak Slough caused water and ice to flow into Aniak. A bombing run of 8 bombs with 7 hits and 1 dud opened both large jams. Several small jams formed below the Kalskags. By bombing the key jam with a run of 8 bombs with 6 hits, 1 miss and 1 dud, this series of jams broke and moved downstream. Jamming occurred below Bethel at the Oscarville Bar and the 10-mile reach from Napakiak to the mouth of the Johnson River was covered by solid ice. An initial bombing run of 6 bombs with 6 hits opened about 50 percent of this area. A second bombing run of 16 bombs with 15 hits and 1 dud opened the remaining area and removed jamming on the Kuskokwim River. The sea ice at the mouth of the Yukon was solid and jamming occurred below Alakanuk. An initial bombing run of 8 bombs with 1 hit and 7 misses was unsuccessful. A second run of 8 bombs with 7 hits and 1 miss removed this jam. A second jam formed opposite Sheldon's Point and was successfully removed with 12 bombs and 12 hits."

"Evaluation of bombing:

"a. Effectiveness: When the bombs are properly placed, the bombing effort is usually successful to a very marked degree.... The effectiveness could be considered very high when bombing accuracy is good.

"b. Safety: Since no personnel are involved in landing or attempting to land directly on the ice jam, and the bombs are normally used only in uninhabited areas, safety can be considered very high.

"c. Accuracy: Although accuracy has improved through experience on bombing operations, there is still a serious problem at times in attempting to get bombs in the proper location. It appears to be primarily a problem of experienced bomber crew, especially since they must bomb by visual means from about a 2,000-foot altitude....

"d. Timeliness: When a jam occurs and threatens a village, the most important element is time. A jam may threaten a village with flooding and accompanying ice problems in a matter of hours....

"e. During the 1962-1966 spring breakups on the Kuskokwim and Yukon Rivers, 11 ice jams were effectively removed by bombing. Numerous smaller ice jams were broken as a result of the bombings. During the 1964-1965 winter operation, bombing was used on the Copper River. The bombing of ice jams caused by single large ice floes has been very effective. Maximum uplift and breaking action was produced with a 500-pound bomb with a delayed fuse time of 0.10 second. A total of 149 bombs with 97 hits, 41 misses and 11 duds were used during the five successive breakups. Bombs classified as duds bury themselves in mud in the bottom of rivers and present no danger."

Froehle (1966) also describes the use of a helicopter.

"Dropping cratering charges from a helicopter into the open water directly above a jam and allowing them to drift under it was also tried. For small single flows this worked fairly well, but, in most cases, the open water was too far from the center of the jam for effective placement of charges."

Moran (1946) describes the use of a helicopter, light plane, and rockets for jam destruction.

Tests were made with a helicopter to determine the accuracy of dropping charges on ice jams. "A 4 x 8 foot panel of plywood was...." used for a target. "A ring-and-pin arrangement was devised for the purpose of releasing the simulated charges from the winch cable of the helicopter as soon as ... (it) had been satisfactorily placed.... Four trips were made to the target, carrying a 100-pound load (50 lb. ea.) each trip. The first load was placed upon the target but was dragged off before the release could be made to function; the next three loads were released directly upon the ... panel."

"Live explosives were dropped manually from the helicopter ... to test the feasibility of dropping primed charges from the ship. Three single 2½-pound primed blocks of Tetrytol were dropped while the helicopter hovered over a sand bar. Then a 60-pound sack of Composition C-3 was dropped on the ice at the edge of the bar. The test demonstrated the safety of dropping the charges from low altitudes and the ability of the ship to safely clear the explosion area."

"At Corning, Missouri, on 8 and 9 February, two 36-pound charges, seven 54-pound charges, three 74-pound charges, and three 160-pound charges of explosives, were dropped on an ice jam from the helicopter. The explosions were observed from a point on the bank approximately three-fourths of a mile away, which was too far to permit close observation of comparative effects (See Figure 2). Most of the ice in the jam was resting on a bar, and there was little or no flow under or through the ice to aid its movement when loosened. Aerial reconnaissance following the test did not disclose any effective results of the blasting, and under the circumstances none were expected."

"The experiment ... demonstrated conclusively: the advisability of beginning blasting operations on a jam before the flow of the stream bypasses the jam; and the difficulty which may be expected in blasting an ice jam once it has become securely grounded. By the time the demolition operations began at Corning, there was little or no flow under the downstream end of the jam. Most of the ice was grounded and the explosives had little if any effect on the jam. Figure 2 shows the relative locations of the main jam, base of operations, and chutes through which the stream was bypassing the jam."

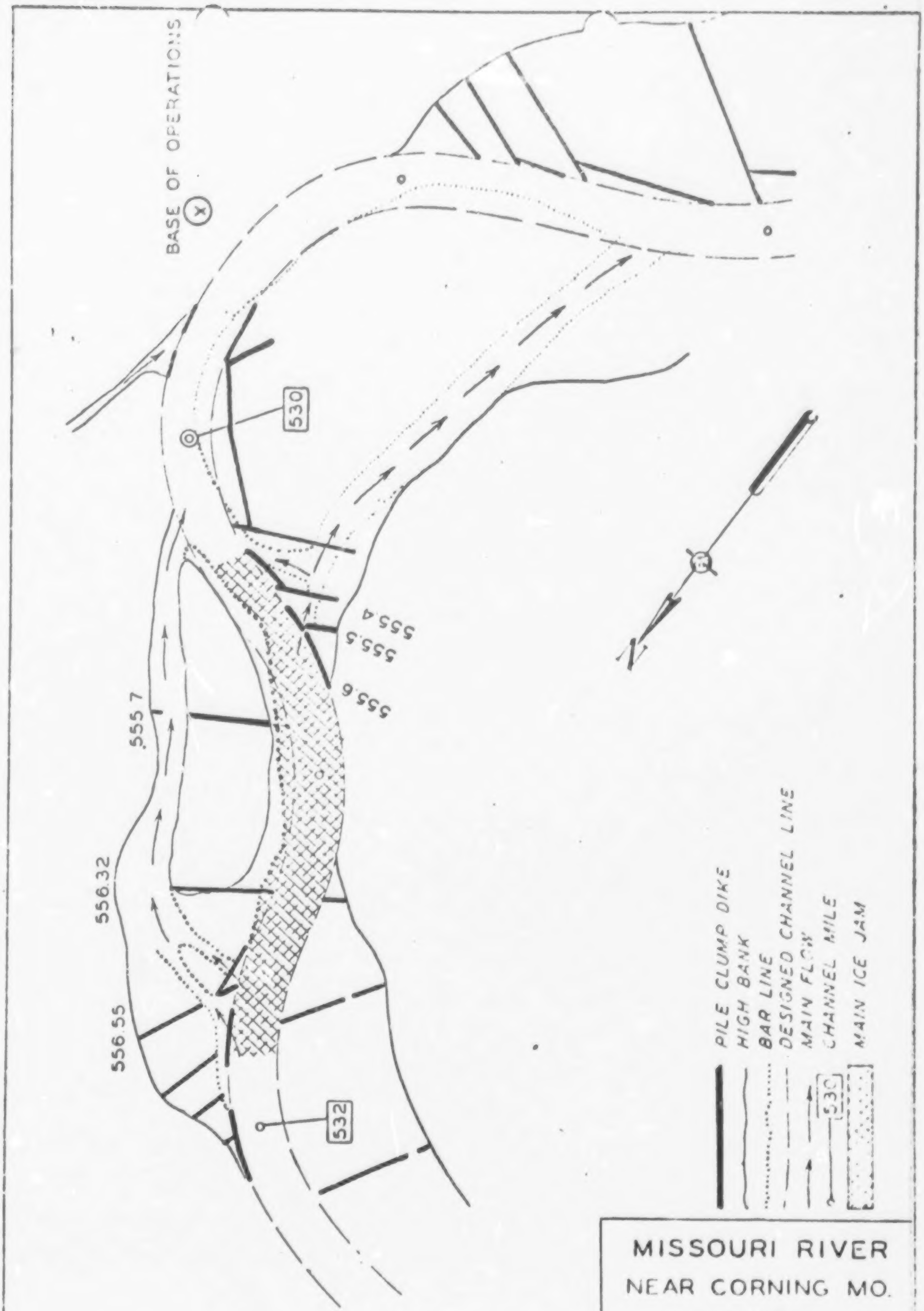
Moran continues by describing tests with a light plane.

"Tests were run ... to determine the accuracy of placement of charges manually dropped ... at altitudes of 20 feet or less. A second test was ... approximately 7½ x 9 feet.... The plane passed over the target on each of its runs at approximately 65 miles an hour, ground speed....

"The tests indicated clearly that placement of charges from a small plane cannot approach the accuracy of placement by means of a helicopter. Increasing the height of the drop from 20 feet or less to 40 feet, appeared to improve the accuracy of original point of impact, but this may have been the normal result of additional practice."

In addition, tests were conducted with T37 Rockets (7.2 inch demolition rocket).

"It carries a 32½-pound charge of explosive in a steel casing, propelled by a motor unit ... attached to the explosive unit before launching. It can be launched electrically from a comparatively simple, portable, two-rail frame mounted on a tripod. The rocket has a maximum range of 300


BASE OF OPERATIONS
X
530
532
555.4
555.5
555.6
555.7
556.32
556.55
N
PILE CLUMP DIKE
HIGH BANK
BAR LINE
DESIGNED CHANNEL LINE
MAIN FLOW
530 CHANNEL MILE
MAIN ICE JAM
MISSOURI RIVER
NEAR CORNING MO.
8 & 9 FEB. 1946
SCALE 1" = 2000 FT.

(Moran, 1946) FIGURE 2

yards and explodes upon impact. It is relatively safe to handle prior to actual launching, as the charge is unarmed until in flight, but upon detonation steel fragments from the casing and motor unit are dangerous to exposed persons within a radius of 600 yards. Operating personnel are safe if they take cover prior to the explosions."

"Eight rockets were used in breaking up an ice jam in DeSoto Bend on 23 February (see Figure 3). Four rockets were exploded on sheet ice six to eight inches in thickness. No appreciable breaking effect was observed from the first three rockets, but immediately following the fourth explosion the sheet ice broke loose 1,000 feet upstream of the target area, and a 1,500-feet section of sheet ice, approximately 500 feet wide, moved out. The experiment was repeated on the heavier jammed ice upstream, with the first two rockets producing no immediately discernible breaking effect, but the third rocket started ice movement approximately 1,500 feet upstream. The fourth rocket in this instance was fired merely to hasten the already obvious break-up. All of the eight rockets used during this test exploded, and the results were highly satisfactory.

"On February, 26, 11 rockets were fired in an effort to remove ice from the upstream side of a dike system in Tieville Bend near Decatur, Nebraska, before it was determined that a bar formation under the ice precluded any possible movement in the direction desired.... The plan of attack was then changed, but the twelfth rocket failed to explode. It lay in sight on the ice and was finally destroyed ... by means of a hand-placed charge.

"The first three rockets fired on 27 February gave good results; they broke up and cleared out a small field of ice that was hanging below the outer end of a dike structure which could not be reached conveniently by other means. A fourth, fifth, and sixth rocket was fired to break up another section of ice, but the sixth rocket went through the ice without exploding. As the unexploded rocket went through the ice into 12 to 15 feet of flowing water and as the ice had been weakened by the preceding two rockets, it was physically impossible to determine the exact location of the unexploded missile. Two additional rockets were fired into the same approximate location. A ninth rocket was later fired to break ice hinging on the end of a dike, but this rocket also failed to explode. It lay in sight on the ice and was eventually destroyed by a propagation charge....

"At this point it was ... concluded ... that the rockets on hand were defective in quality....

"The writer is not qualified to determine the cause of failure of some of the rockets to explode, but it is interesting to note, even if coincidental, that the rockets performed more reliably as the temperature increased....

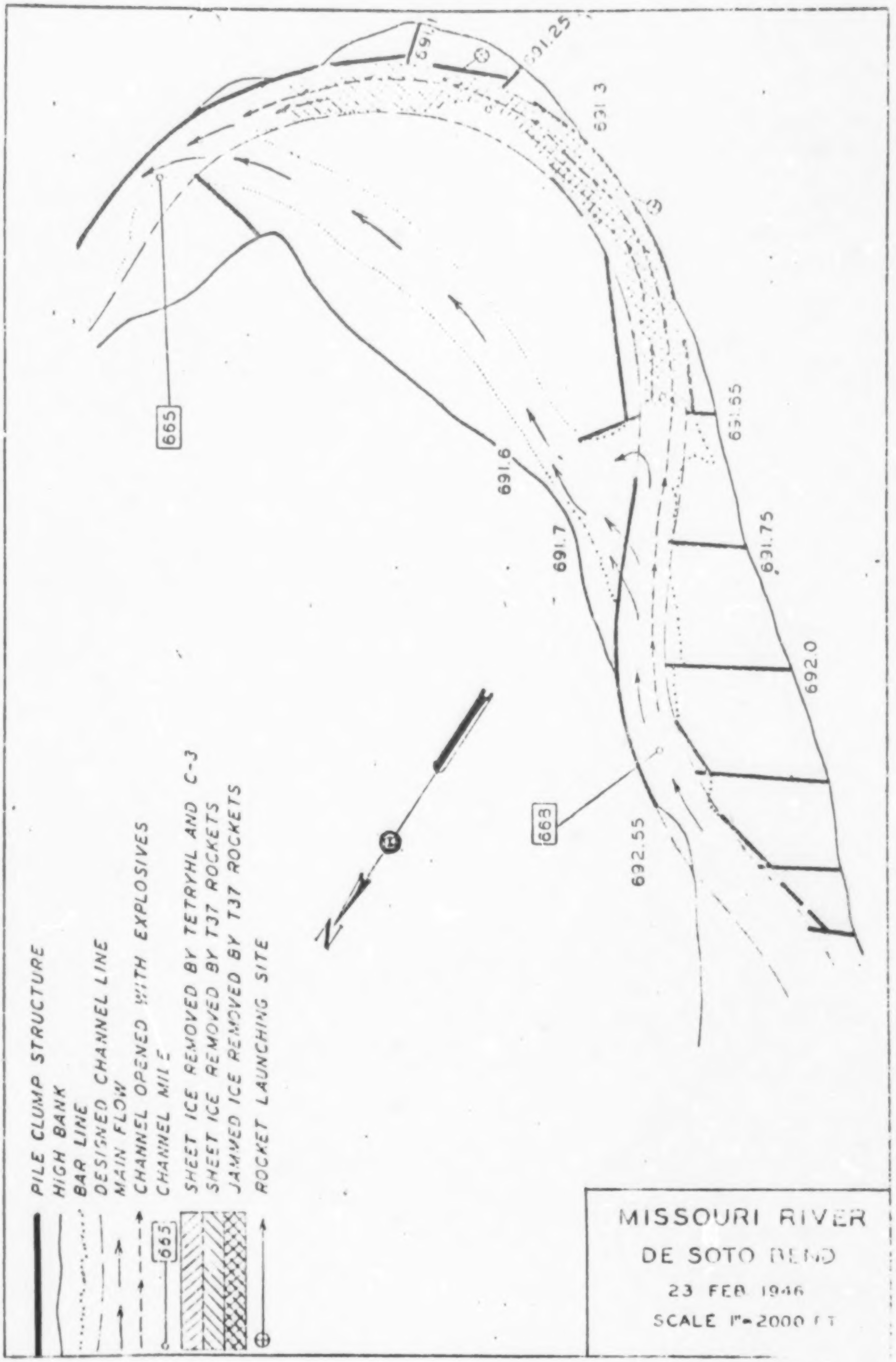

PILE CLUMP STRUCTURE
HIGH BANK
BAR LINE
DESIGNED CHANNEL LINE
MAIN FLOW
CHANNEL OPENED WITH EXPLOSIVES
CHANNEL MILE
SHEET ICE REMOVED BY TETRYHL AND C-3
SHEET ICE REMOVED BY T37 ROCKETS
JAMMED ICE REMOVED BY T37 ROCKETS
ROCKET LAUNCHING SITE
665
663
691
691.25
631.3
631.65
631.75
691.6
691.7
692.0
692.55
N
MISSOURI RIVER
DE SOTO BEND
23 FEB 1946
SCALE 1"=2000 FT

FIGURE 3

(Moran, 1946)

"The signal success obtained from use of the rockets in the DeSoto Bend operation and in Tieville Bend, up to the point where they failed to explode and were condemned, indicated that: (1) Rockets could be fired faster than comparable hand charges could be placed; (2) They could be placed with reasonable accuracy in places on an ice jam which could not be reached by any other means except by helicopter; (3) They had a greater concussion effect on the ice than did a comparable charge of Tetrytol or Composition C-3."

In obviously favoring the use of rockets as opposed to Tetrytol and C-3 (see Surface Explosives) he continues to describe operations on the DeSoto Bend jam.

"... The small hand-cast charges of Tetrytol and Composition C-3 accomplished the removal of 2,000 feet of sheet ice, approximately 500 feet wide, in 68 minutes. In comparison, four T37 rockets removed an additional 1,500 feet of similar ice in 15 minutes. Even more spectacular success was attained by use of the T37 rockets on the main jam, when three rockets fired onto the lower end of the ice actually broke the jam and started approximately 5,000 feet of jammed ice moving downstream within 14 minutes. A fourth rocket was fired to hasten the already well developed process of breaking up, but it probably was not necessary."

In another report on the same operation, Dantone (1946), feels that the rockets were "useful for the demolition of ice jams but require modification ... by the addition of a self-destructor fuse, and by fabricating the casing of plastic or fiber."

Reports on the use of aerial explosives in foreign countries are usually brief and void of details of results. Some of these are given below as evidence that the methods have been attempted on a worldwide basis.

In one of the most recent articles LeiBen'-fu (1954) briefly describes measures against spring flood damage on the Hwang Ho in Mongolia. "Measures taken included ... the use of bombs and artillery to break up the ice jam." The initial artillery shell was fired from a range of 50m and that within a half an hour the jam was breached so that flood waters could pass through.

Laktionoff (1957) reports on ships which were trapped on the Lena River. "Bombing from the air was employed among other means for the demolition of ice-jams that were considered dangerous for the ice-bound vessels." He states that other methods were employed to eventually free the vessels.

Van der Kley (1965) reports that: "in the winter of 1940/1941 the Germans tried bombarding ice from aircraft. One of the bombs struck the ice 80 meters below a bridge, luckily without exploding. Five other bombs also failed to explode. None of those duds were ever found."

"Although the idea of bombarding ice and attacking it with rockets from the air would seem an attractive proposition because it can be done with greater safety to those employing the method, it is open to grave objections because it is difficult to control. The risk of projectiles not exploding when they hit ice is very great indeed, and as it is very difficult to find duds again, the method is condemned; it would constitute too great a hazard to shipping."

Antrushin (1956) feels that bombing on Russian rivers was effective, "but is harmful to the fishing industry."

Bock (1957) does not favor the use of aerial explosives. From observations on the Danube, Elbe, Oder and Vistula, he recommends ice-breakers.

"All attempts to fight compact ice jams by blasting, gun fire, aircraft bombs, etc., have practically been of no avail. In certain cases local success could be met within ice accumulations but in general there are no efficient technical means known of safely preventing the formation of ice impacts."

Aerial explosives

Antrushin, N. (1956) Samolety razrushaiut led (Airplanes demolish ice), Grazhdanskaya Aviatsiya, vol. 13, no. 4, April 1956, p. 33 (text in Russian). English translation by U. S. Lake Survey, Detroit 1967.

Bock, H. (1957) Ice-breaking on navigable rivers with and without power plant ponds, 19th International Navigation Congress, London 1957, sect. 1, commun. 3, p. 37-50. Reprinted by courtesy of the Permanent International Association of Navigation Congresses.

Brady, W. D. (1947) Galena ice jam bombing report, Hq. 57th Fighter Group, Alaskan Air Command, AAF, copy from: Air University Library, Maxwell Field, Alabama, 9 p.

Dantone, P. F. (1946) Research toward breaking up of ice jams, Engineering Research and Development Lab., July 22, 1946, Report 984, 78 p.

Froehle, Lt., H. A. (1966) ANFO in the Artic, Copyrighted by The Society of American Military Engineers. Reprinted by permission from The Military Engineer, Jan.-Feb., 1966, p. 16-18.

Hendry, W. B. (1943) Bombing of ice jams, Memorandum in files Hq., Test Section, Cold Weather Testing Detachment, Ladd Field, Alaska, dated 24 May 1943.

Henry, W. K. (1965) The ice jam floods on the Yukon River, Weatherwise, April 1965, vol. 18, no. 2, p. 80-85.

Jessen's Weekly (1949-1950) Fairbanks, Alaska, editions of 10 June 1949 and 8 Dec. 1950.

Laktionoff, A. F. (1957) The effects of ice upon shipping routes, sea and river ports, and the means to combat it, Proceedings, 19th International Navigation Congress, London 1957, sec. 1, commun. 3, p. 177-217. Reprinted by courtesy of the Permanent International Association of Navigation Congresses.

Lei Ben'-fu (1954) Bor'ba s zatorami l'da (Control of ice jams), Kitai (Peking), May 1954, no. 5, p. 9-10 (text in Russian). English translation by U. S. Lake Survey, Detroit 1967.

Moran, J. J. (1946) *Memorandum report on research toward breaking up of river ice jams*, U. S. Army Engineer District, Omaha, Corps of Engineers, 1946, 22 p.

Pewe, T. L. (1948) *Terrain and permafrost, Galena area, Alaska*, Permafrost Program Progress Report No. 7, U.S.G.S., for: Eng. Intel. Div., Office, Chief of Engineers, U. S. Army, (Restricted).

Reed, P. L. (1945) *Report on Yukon River break-up*, Memorandum in files of U. S. Army, Alaskan Div. Air Transport Command Hq. 1466th, A.A.F. Base Unit, dated 1 June 1945.

Rock Island District, Corps of Engineers (1967) *After action report, Ice conditions - winter of 1965-1966, Appendix E, Activities of Alaska District*, U. S. Army Engineer District, Rock Island, Corps of Engineers, 11 p.

University of Minnesota (1950) *Investigation of airfield drainage, Arctic and Subarctic regions, part I, prepared under contract with U. S. Army Engineers District*, St. Paul Corps of Engineers, for: Office, Chief of Engineers, U. S. Army, October 1950 (Restricted).

Van der Kley, If. J. (1965) *The use of explosives for clearing ice*, Rijkswaterstaat Communication, Nr. F 1965, 55 p.

Williams, J. R. (1953) *Break-up and freeze-up of the Yukon River at Beaver, Alaska*, Engineering Notes no. 31, U. S. Army Engineering Intelligence Division, January 1953, 57 p.

River Modification

River modification pertains to alterations of the normal flow pattern of a river for the purpose of preventing or removing ice jams. Flow patterns are regulated by modifications to the channel, by reservoirs, and by ice retention or diversion structures.

River modifications are normally designed to prevent the damages experienced in previous ice jams in the region. It is also possible that unusually massive ice jams will occur subsequently. Ice modification techniques as described previously are then employed to prevent damages. Foulds (1967) comments: "While the cardinal rule for this river is to keep the ice moving downstream until it reaches Lake Ontario, and rules based on velocities and other criteria have been developed for the prevention of jams, it has nevertheless been found advisable to provide means for overcoming ice jams in recognition that some will occur."

Ice retention & diversion structures

Ice booms and control structures used primarily for ice retention (as opposed to surging) are included here. The conventional boom and booms constructed from natural river ice are discussed. The theory of both types is successful river ice grouping in non-critical locations. It is interesting to note that considerable success is reported by users of ice booms. Papers which describe ice dams, submerged weirs and diversion structure are also included.

Michel (1965) describes the general types and functions of ice control structures.

"Goal of the structures

"The ice control structures in rivers for the spring break up can have essentially two goals:

1 - Stabilize the ice field, by retarding the removal of ice blocks from chosen sites;

2 - Accumulate the ice floes and melt them in place.

"The structures of these two types can be used separately or concurrently to reduce or remove the risk of spring ice flooding on a section of a river. Suppose, figure 7, a river composed of a section of strong slope A, followed by a section of weak slope B, and a final section of strong slope C. Section B generally will contain many

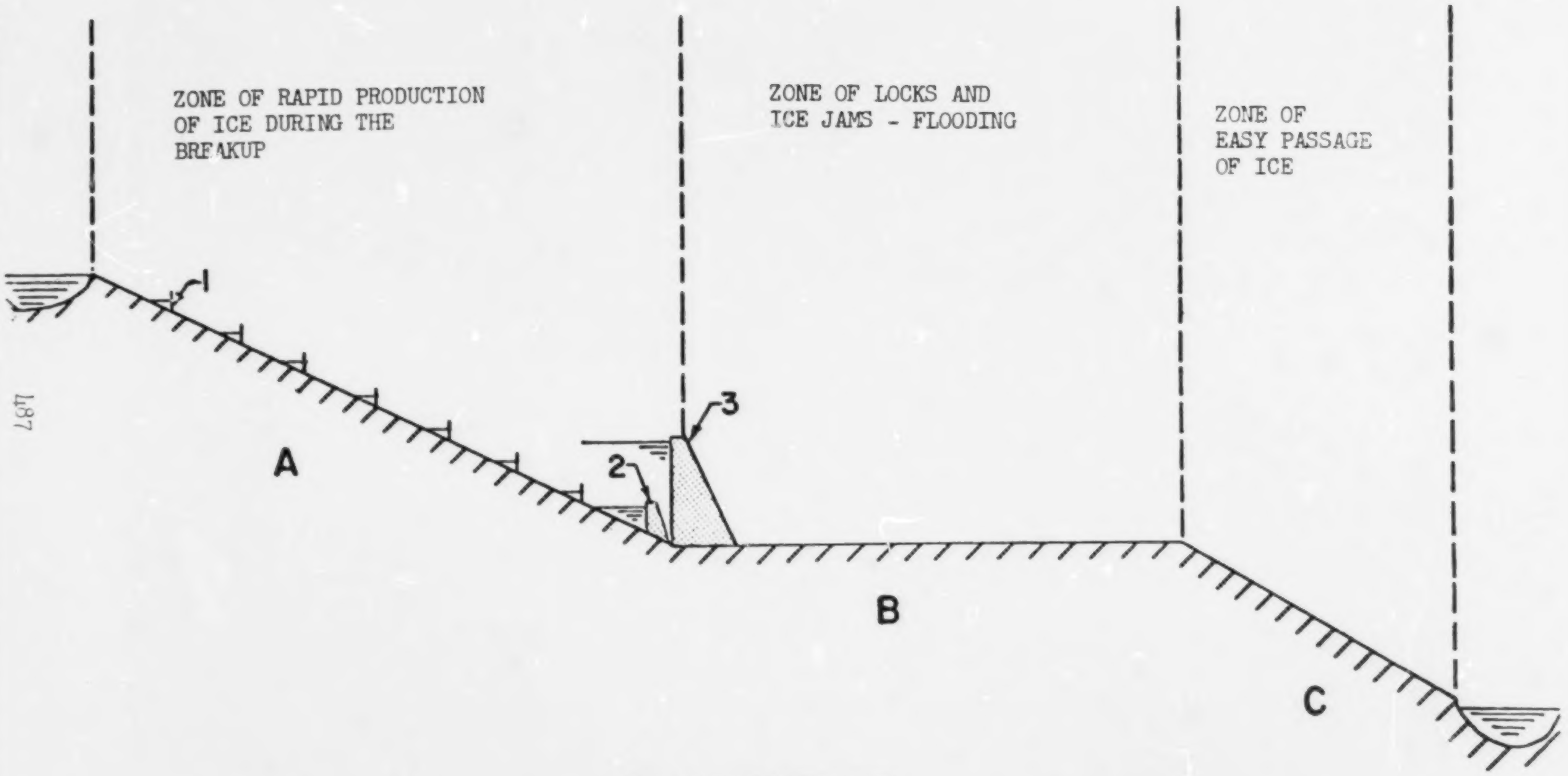

ZONE OF RAPID PRODUCTION OF ICE DURING THE BREAKUP
ZONE OF LOCKS AND ICE JAMS - FLOODING
ZONE OF EASY PASSAGE OF ICE
1
2
3
A
B
C

FIGURE 7

ARRANGEMENT OF ICE CONTROL STRUCTURES FOR THE BREAKUP - TYPICAL RIVER (Michel, 1965) meanders, curves and irregularities. Section A will be brutally freed of ice which will arrive all at once in B. Ice passage in Section B will be difficult; numerous locks and ice jams will be formed. This will be a flood-danger zone.

"The structures of stabilization (1 or 2) of the ice field, situated in zone A, are proposed to retard the release of ice stabilizing the locks until a discharge higher than normal can be obtained. One then can expect that the ice field in section B will have time to descend before the arrival of the delayed ice from section A. When they (ice from section A) are presented they will not have time to form a solid mass of locks and they will proceed to section C without halting, then without difficulty towards the mouth. The flooding in B will then be considerably reduced.

"A drastic solution would be the construction of an accumulation dam (3) at the foot of rapid A, in such a way as to retain all the ice and not to let it pass, so that it will melt in place. Thus, it is physically impossible for them to contribute to floods in B.

"Principle of functioning of the structures

"At a given site on a river exists a level-discharge relationship (0) represented on figure 8. At this same site one can indicate the relationship of the limit of crushing of a lock.

"At the junction of these curves, that is to say, when the discharge becomes equal to q_o it can no longer have there (at that point) a lock and the latter must succumb.

"Construct, at this site, a structure which raises the water level and from which the discharge relationship is represented by curve (1). It is necessary to have a discharge of q_1 before the lock will succumb. The discharge q_1 is above q_o and the structure will now be permitted to retard the passage of the lock, for the time necessary, on the hydrogram, to pass from q_o to q_1. This structure is now a structure retarding the ice drift at this site.

"Finally if one builds a structure whose discharge relationship is given by (2) and from which the discharge at the crushing (breaking) of the lock q_2 is over that of the increased discharge of the river, it is clear that this structure can retain the ice at all times and allow it to melt in place.

"This is the principle of functioning of the ice control structures. In addition it is also necessary:

- that the structure presents a physical obstacle to the passage of the ice at the level of stoppage, to initiate the lock;

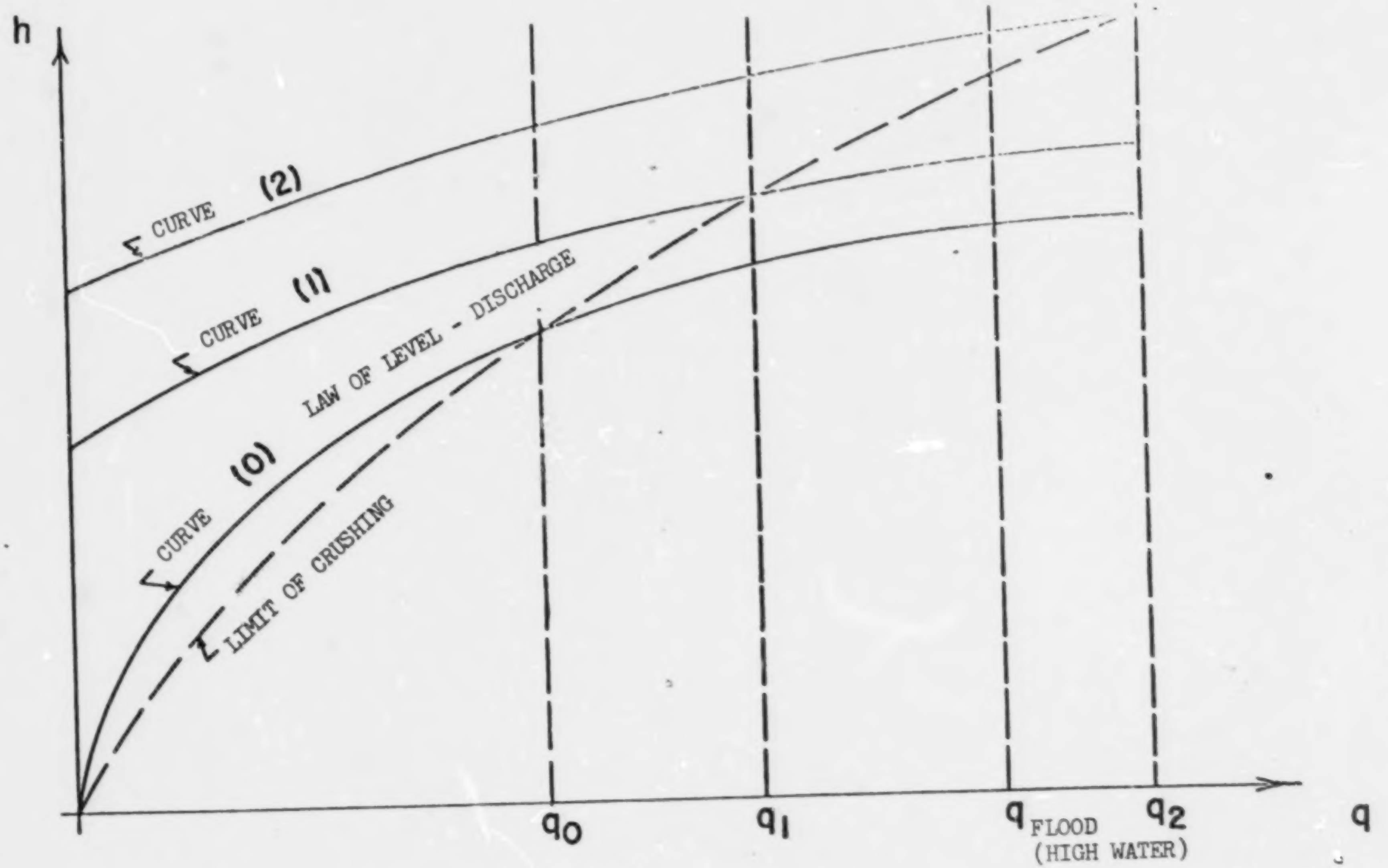


FIGURE 8

PRINCIPLE OF FUNCTIONING OF THE ICE CONTROL STRUCTURES (Michel, 1965)

IN A RIVER AT THE SPRING BREAKUP

- that the structure draws to accumulate in the stoppage the quantity of ice coming from upstream;

- that the lock becomes stable not only at the right of the structure but also in the stoppage properly so-called.

"The Structures

"Here, we will hold ourselves to ice booms, sluice dams and diversion dams.

"Ice booms combined with submerged sills (figure 9) are excellent for retarding local ice drifting. For slight depths rock weirs are particularly economic. The ice boom itself is set to start the lock and presents the enormous advantage that it can release and pass the ice floes if the water levels upstream rise in an unexpected manner.

"Sluice dams (figure 10) have the advantage of not producing frazil during the winter since there is little loss of force (hence warming the water) between the two pools. Their relations of discharge (that at the mouths) permits stabilization of locks for all discharges. Unfortunately the water levels are weak in retention at the start of the ice drift and the smallest ice blocks are easily passed toward the bottom openings, blocking them. It is nearly impossible to dislodge them....

"Diversion dams (figure 11) seem very well adapted for the retention and accumulation of ice. A grill must be constructed upstream of the weirs for retention of the latter (i.e. the ice)."

A recent report by Foulds (1967) describes the effectiveness of an ice boom.

"Many changes have been made to improve the ice carrying capacity of the (Niagara) River and many unusual features are included in the water diverting intakes and the ice handling equipment.... The most significant change of all came about when an ice boom was installed at the outlet of Lake Erie. This paper describes the ice problems ... before and after the installation of the Lake Erie ice boom."

"...The factors causing the greatest difficulty in the past were strong winds over Lake Erie from the southwest to west after the lake had partially frozen, or during the period in which a natural ice bridge was forming between Buffalo and Fort Erie. In an average year approximately four weeks elapsed after ice started to form in Lake Erie before the ice bridge gained sufficient strength to hold the ice in the lake....

"From experience gained by observing the operating characteristics of ice booms installed by Ontario Hydro and the Power Authority of the

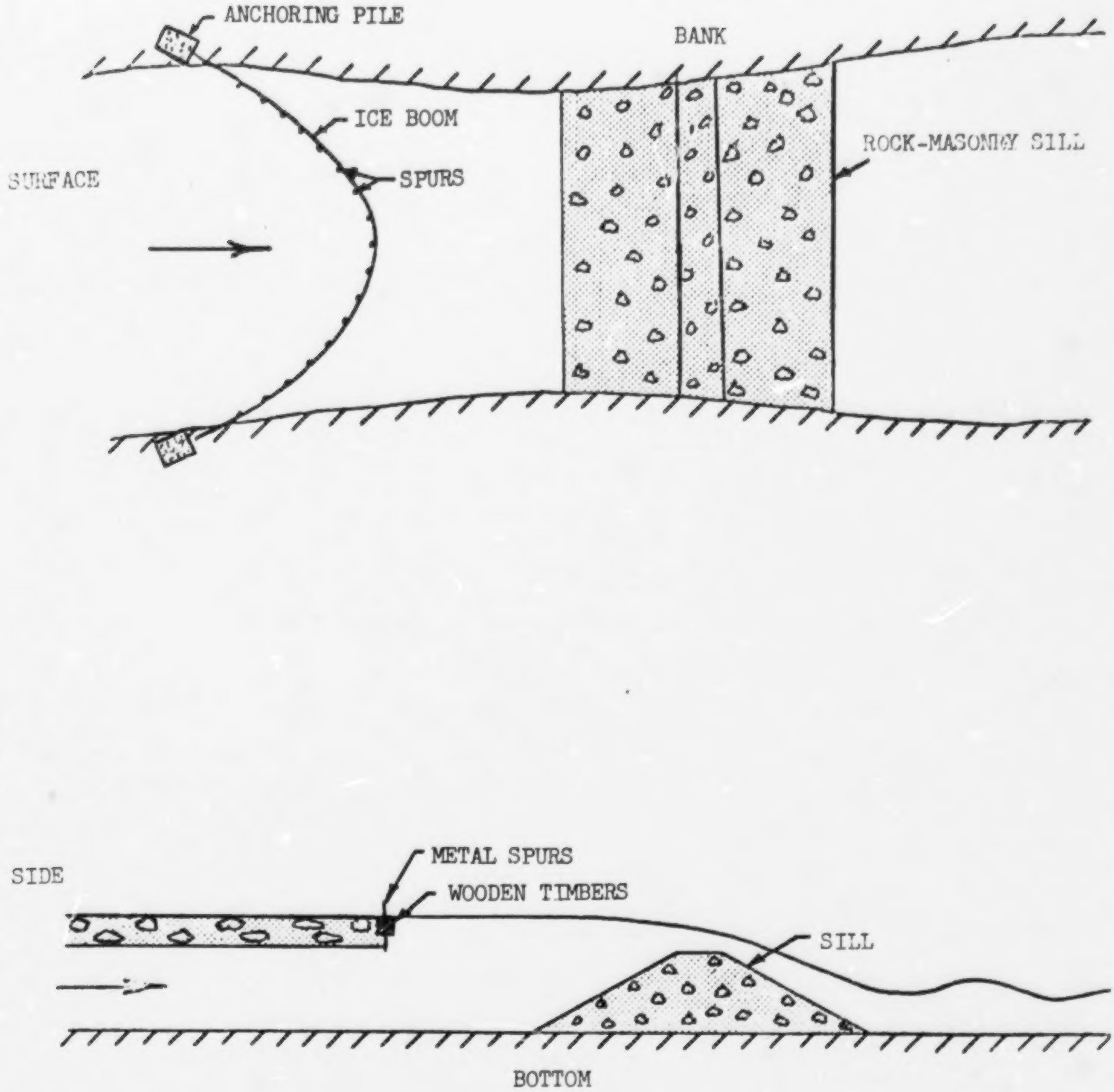

ANCHORING PILE
BANK
ICE BOOM
SURFACE
SPURS
ROCK-MASONRY SILL
SIDE
METAL SPURS
WOODEN TIMBERS
SILL
BOTTOM

FIGURE 9

ICE BOOM FOR CONTROL OF ICE (Michel, 1965)

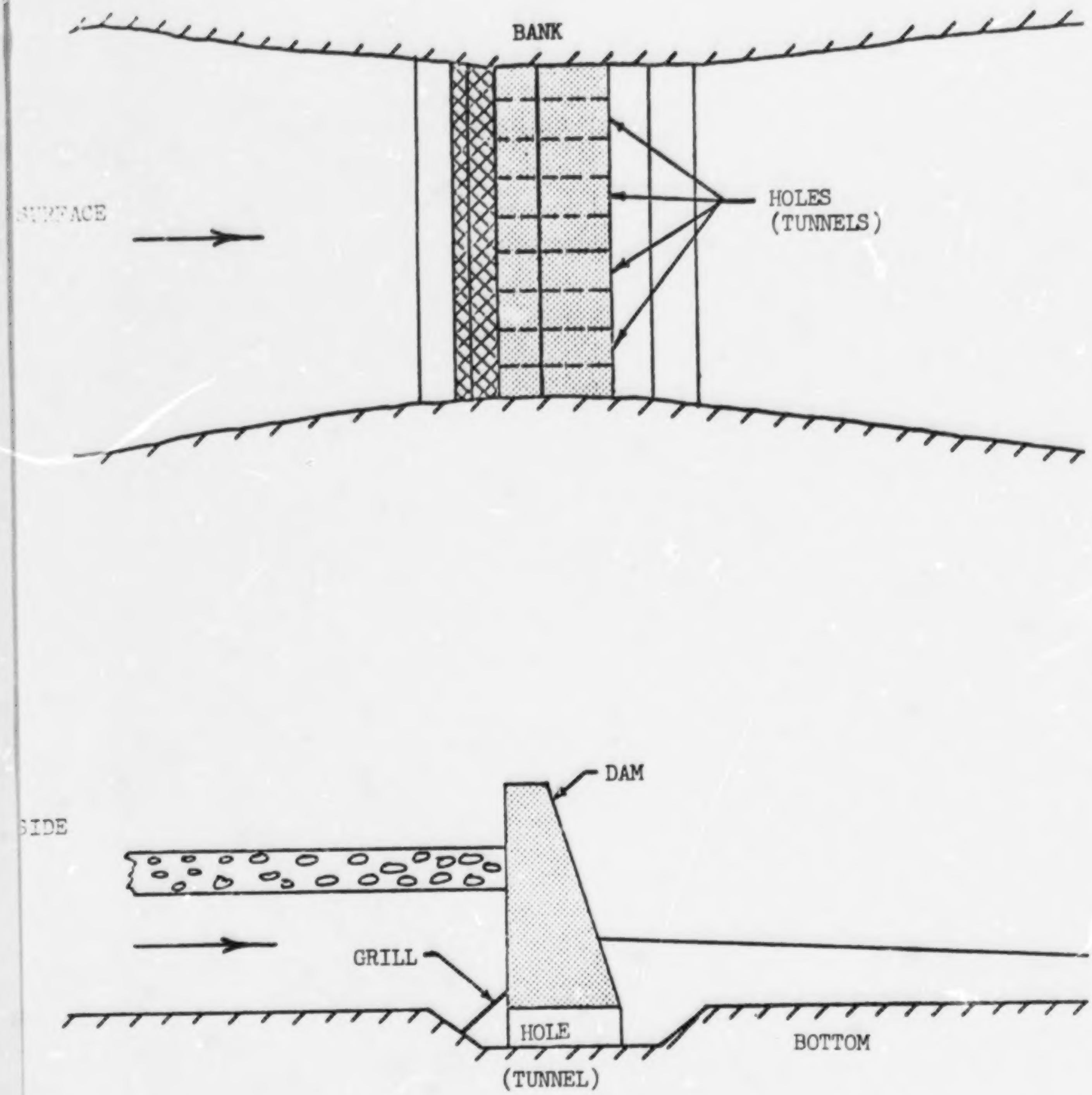

BANK
SURFACE
HOLES
(TUNNELS)
DAM
SIDE
GRILL
HOLE
(TUNNEL)
BOTTOM

FIGURE 10

PIERCED DAM (TUNNEL DAM) FOR CONTROL OF ICE (Michel, 1965)

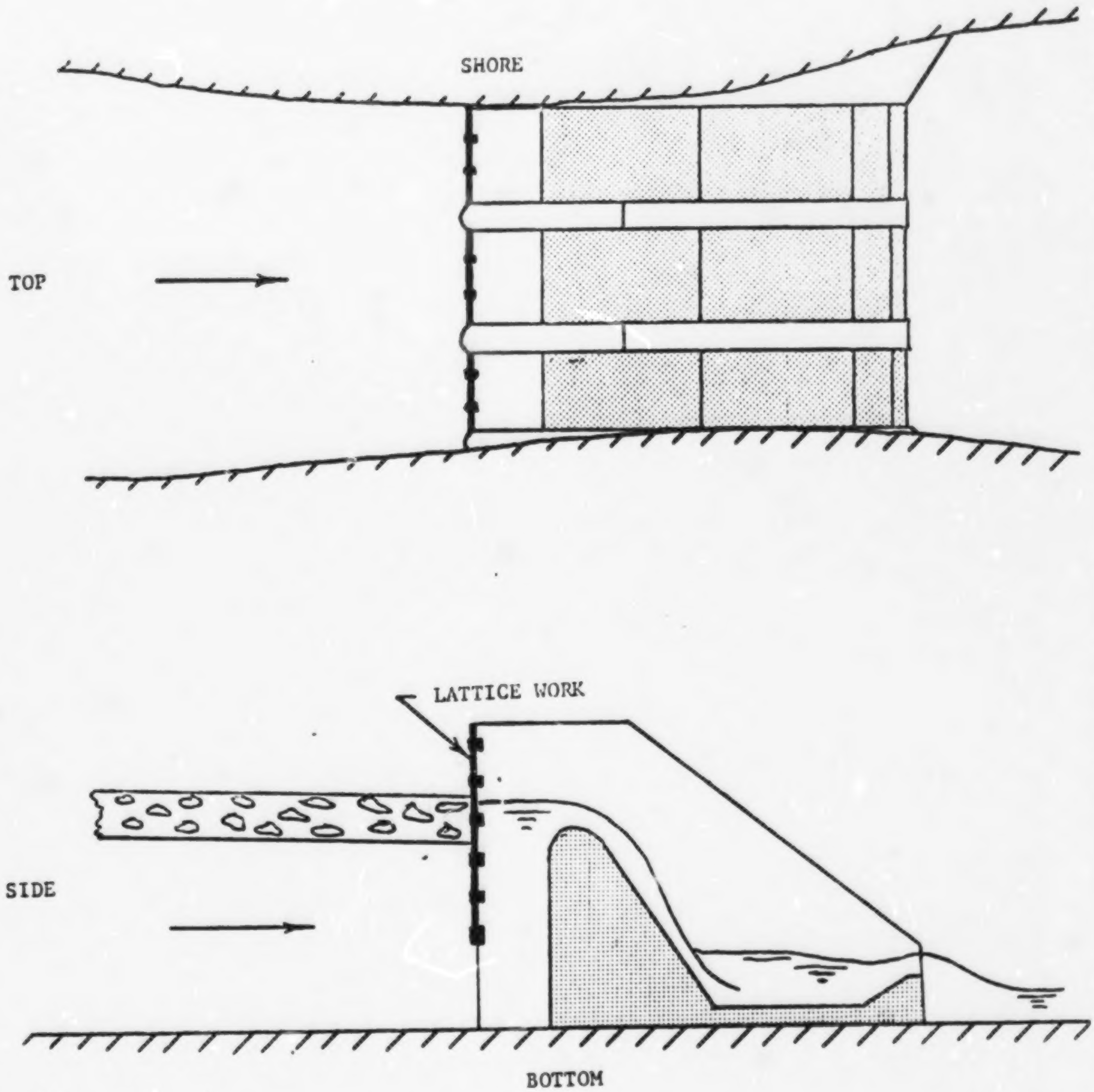

SHORE
TOP
LATTICE WORK
SIDE
BOTTOM

FIGURE 11

OVERFLOW DAM FOR THE CONTROL OF ICE (Michel, 1965)

State of New York in the International Rapids Section of the St. Lawrence River, it appeared that a similar boom would have a number of beneficial results in controlling the Lake Erie problem. Accordingly, in 1964 the two Power Entities requested and received permission from the International Joint Commission to install an ice boom, two miles in length, between Buffalo and Fort Erie. Its purpose is to accelerate the rate at which the ice arch forms between the shores and to stabilize the arch once it has formed. The boom is not designed to prevent all the ice from leaving Lake Erie but to vastly reduce the quantity of this ice. It is not feasible to prevent the ice cover in this lake from moving under the influence of a storm because the water level may rise as much as six feet which is more than sufficient to break any shore restraint. Under the influence of the wind most of the eastern portion of the lake ice surface, moves forward until it wedges...against the shore at the new water level. In the process the ice surface may break into huge slabs and those touching the boom may be pushed over the top. After the storm subsides, the boom comes back to the surface as the result of its own buoyancy and cuts off the flow of loose pieces.

"So far, the boom has reduced the number of days in which ice used to pour out of Lake Erie to the corresponding number of hours. There has not yet been a storm of equivalent intensity to those which produced the most massive ice runs of the past, however the boom has held back all but minor quantities of ice despite a rise in level of 5½ feet and winds of 35 mph and there is reason to expect from its performance to date that it will continue to be successful."

The winter of 1965 "...was the first year of operating experience with the Lake Erie ice boom in place. Winter arrived very late, and the cover did not begin to form on Lake Erie until after the middle of January. By January 21, the ice cover extended approximately 8 miles to the west and was measured as being 6 inches in thickness one mile upstream from the boom. The weather was not sufficiently cold to properly consolidate the cover and on January 23 all but 2½ miles of the cover was shifted westward by the wind leaving a strip from shore to shore resting against the boom.... On January 26....a severe storm developed during the evening with winds of more than 35 miles an hour gusting to 70 miles per hour. During this storm the Fort Erie water level rose 5½ feet in four hours and the flow out of the lake increased by more than 100,000 cfs with the result that some ice moved over the boom as expected. No difficulties were encountered in passing the ice which came out of the lake down the river to Lake Ontario, and the boom restricted the duration of the run to a few hours rather than several days...."

The winter of 1966 "...was in many respects similar to that of 1965, when the ice cover again did not begin to form on Lake Erie until after the middle of January. On January 27 a rise of three feet took place in the water level at Fort Erie under the influence of winds up to 34 miles per hours. Although the ice behind the boom was still relatively thin, no ice came over the boom on this occasion."

Strowger (1946) describes the use of ice booms over water power intakes on the Niagara River and channel dredging to reduce flow velocity under ice booms.

Groat (1920) describes the use of an ice boom by a power company.

Triquet (1967) describes experiments to develop on ice control structure for the Chaudiere River.

"View of the Assembled Problems

"Properties along the Chaudiere River have been subjected for a number of years to important damage caused by the effects of ice from the spring breakup. Several studies and observations have been made on this subject, and most of them are contained in a report which can be obtained from the Minister of Natural Resources of Quebec (Triquet, 1965).

"In review, the principle conclusions of this report are:

1. The long profile of the Chaudiere River can be divided into four characteristic sections (see fig. 1, Deslauriers, 1965) the source part of the section has a strong slope, followed by a central part comprising an intermediate section followed by a zone having very weak slope and finally the last part having an accentuated slope.

2. The strong slope of the upper section, made more so because the river flows from south to north, makes this section lose its ice or this section breaks up its ice before the sections of the central part. The weak slope at its bottom and the numerous irregularities make the evacuation of the ice blocks at the breakup very slow and difficult. The preceding factors are the principle causes which provoke the ice jams and the ice from the upper part comes to butt itself against the ice field still solidly in place."

"Stockade for Retention of the Ice

"A dam of a special type ... having as its function the retention of ice from the upper part, it remained to find a way to arrest the ice coming into the intermediate section: on the contrary it was necessary to consider the danger of flooding the section by accumulation of ice on its downstream extremity. The construction for the retention of ice considered to be adequate was a floating breakwater and a submerged sill: the advantage of this type of construction is that one does not necessarily retain all of the ice, but a certain quantity which can be controlled by varying the height of the submerged sill. It was necessary then to determine the characteristics of the breakwater sill system for which the sum of the costs of the damages is minimum, in considering the damages caused upstream by the retained ice, and that caused downstream by the ice which passes. An excellent site for the installation of this type of work, the Rapides du Diable, is situated one-half mile upstream from Beauceville: there is found a zone of rapids about 4000 feet long followed by a large basin. To determine the characteristics of the breakwater sill system a model study was undertaken....

"A length of river 6,000 feet including the rapids and the basin was reproduced at a scale of 1/125. After several observations of ice jams and the sounding of the ice field, the following values were deduced: average dimensions of 6 feet by 6 feet by 2 feet for the blocks of ice at an average thickness of 3 feet of the ice field, the total volume of ice carried 40 x 10^6 cubic feet. The ice blocks were reproduced in polyethelene at the average scale, of the same density as the ice and given a surface roughness adjusted with fine sand. The heights of the water, on the model, were adjusted in 10 sections to 3 values of discharge.

"A first series of experiments was conducted to recognize the capacity of the natural retention of the ice field, which was represented by way of a small metal strip fixed to the shores and reproducing the thickness of the ice field. The resistance of the field was considered as broken as soon as the hydrodynamic conditions forced the blocks of ice to pass under the metal strip.

"The experiments began without the sill and gradually raising the height of the sill. The experiments revealed that the phenomenon of arresting the ice is not generally progressive and continuous."

Because of the pronounced narrowing of the section of flow at the point of stoppage, the evacuation of the ice was made in a quick and sudden fashion, and the accumulation formed itself into a soft or sweet ice jam (accumulation of the ice to the bottom and passage of the discharge by infiltration).

Llamas (1965) gives details of an experimental ice boom on the Chaudiere River which was apparently built according to the model tests described by Triquet in the above paper.

"The experimental boom at Drolet, such as was projected and constructed contained the following elements:

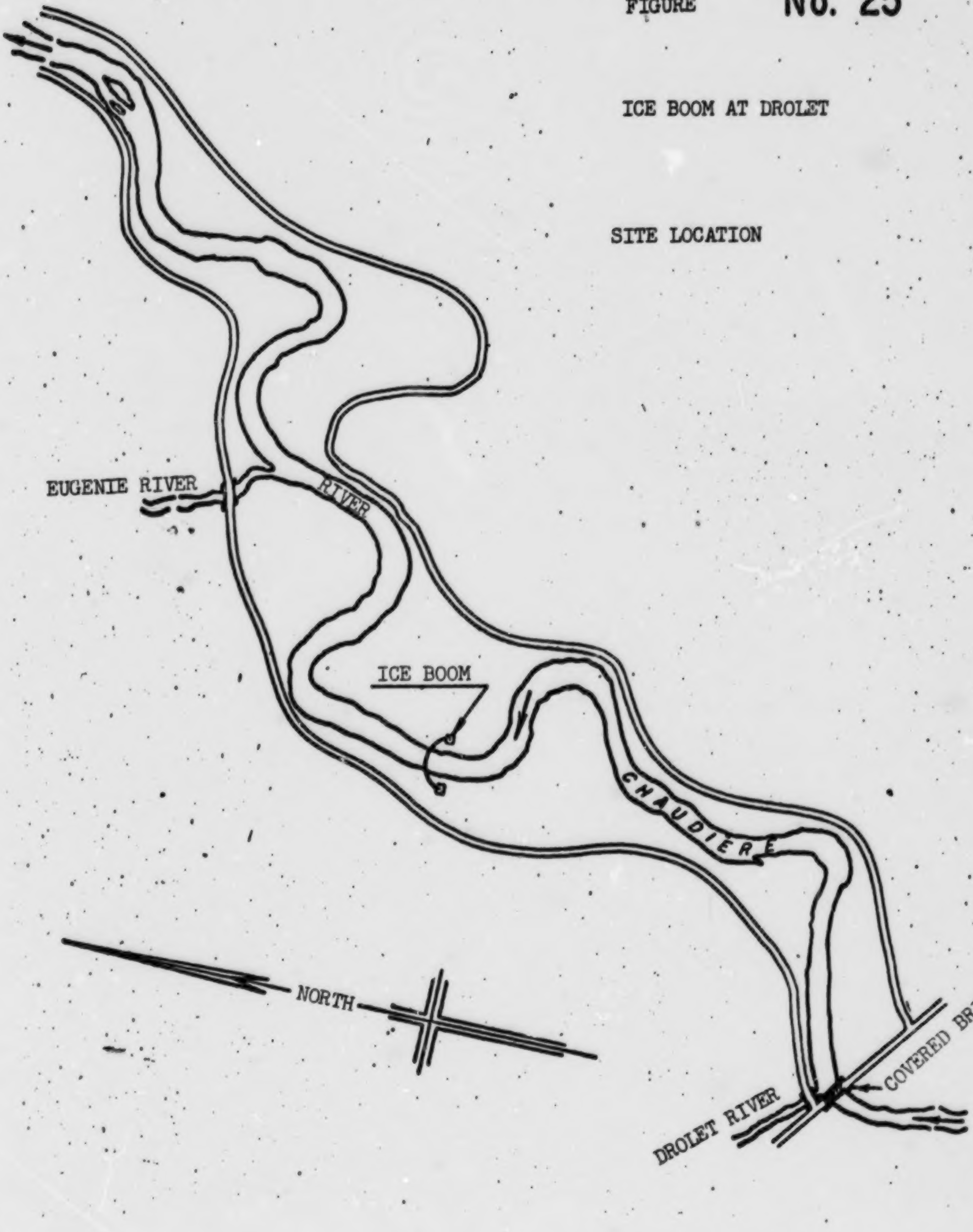
1. A rock sill 140' long and 5' high,
2. Two anchorage pilings of re-enforced concrete,
3. A boom composed of two steel cables with wooden floats,
4. An earthen dike on the right bank 300' long (Figs. 25, 26, 27).

"The rock sill created a reservoir of tranquil water which favored the formation of a static ice jam and at the same time assured the floatation of the boom.

FIGURE **No. 25**

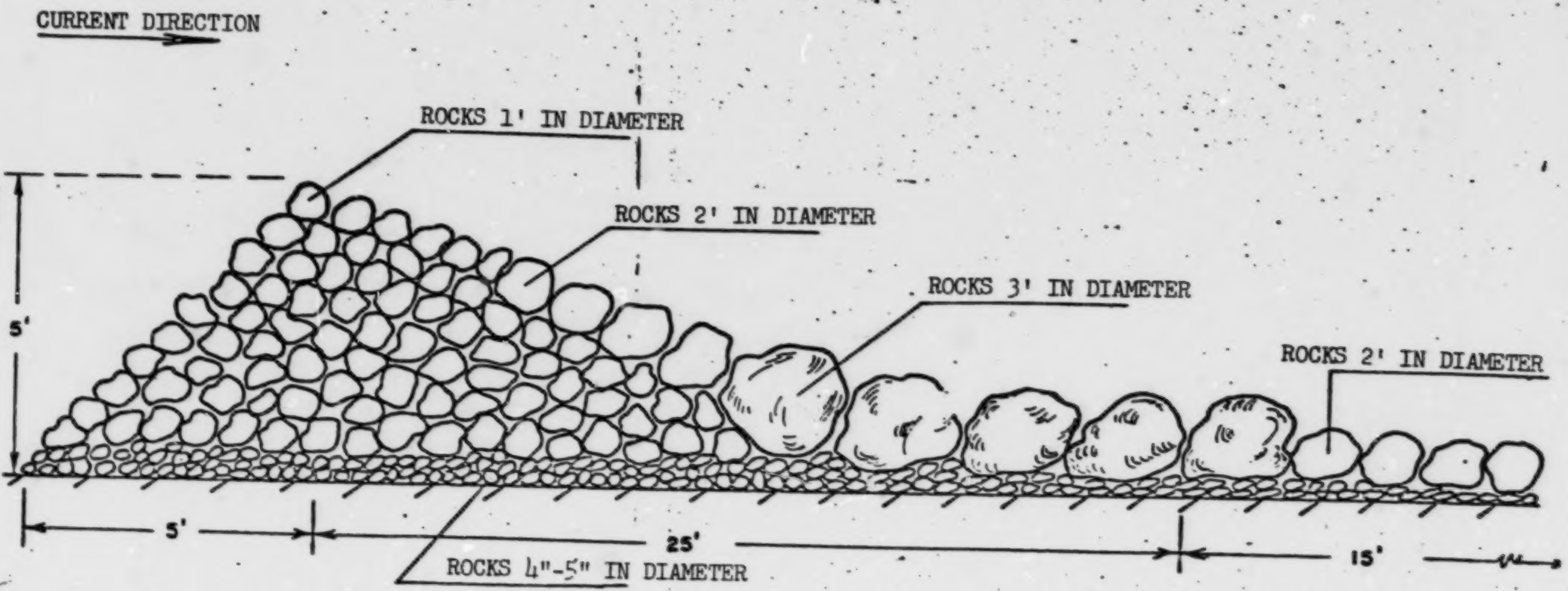
ICE BOOM AT DROLET

SITE LOCATION


EUGENIE RIVER
RIVER
ICE BOOM
CHAUDIERE
NORTH
COVERED BRIDGE
DROLET RIVER

(Llamas, 1965)

FIGURE **No. 26**


CURRENT DIRECTION
ROCKS 1' IN DIAMETER
ROCKS 2' IN DIAMETER
ROCKS 3' IN DIAMETER
ROCKS 2' IN DIAMETER
5'
5'
25'
15'
ROCKS 4"-5" IN DIAMETER

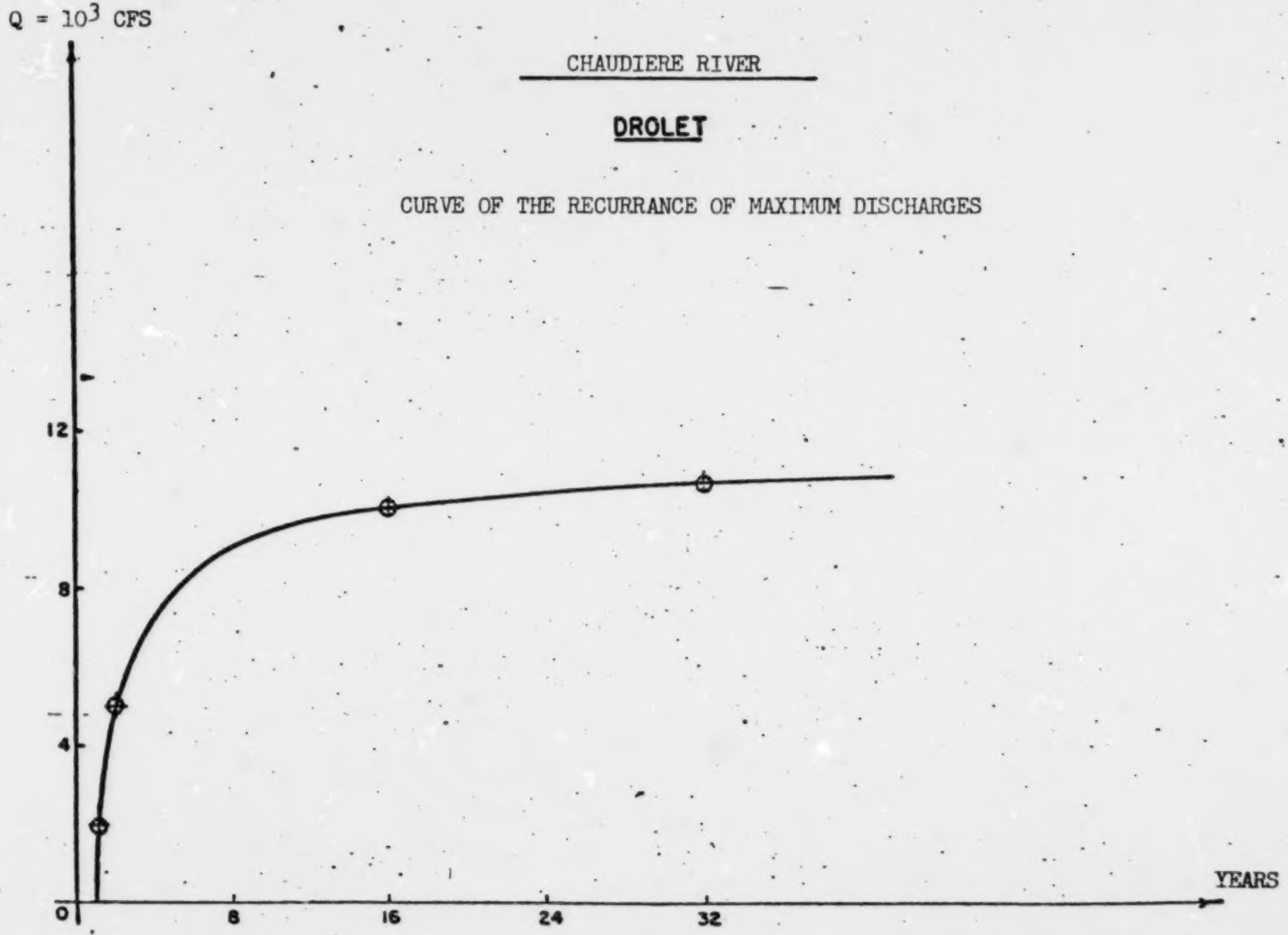
TRANSVERSE SECTION OF THE ROCK SILL AT DROLET (Llamas, 1965)

FIGURE **No. 27**

CHAUDIERE RIVER

DROLET

CURVE OF THE RECURRANCE OF MAXIMUM DISCHARGES



(Llamas, 1965)

"The height of the sill was fixed at 5 ft. to maintain an acceptable limit to flooding of the shores, with and without ice, and also to create a sufficient volume or area to retain the accumulation of ice coming from upstream. Thus the boom will retain the ice until a discharge, during the period of breakup, of 73000 cfs. is reached (discharge corresponding to a period of recurrance of 4 yrs. See figure 27). Beyond this the value of the floods will be very important. The calculation of the equilibrium of the static ice jam behind the boom shows that this accumulation will become unstable and that it is necessary to break it to pass under the construction.

"Figure 28 shows the form and the evolution of the ice jam behind the boom such as seen, corresponding to a discharge of 7300 cfs. In this figure, the line AD is the water level with a winter ice cover, without an ice jam. At the breakup, the maximum ice jam EF of maximal elevation of 11 ft. in 700 ft. can be located on all points of AD. The maximum possible level is now the line ABC.

"The volume of accumulated ice, taking into account a coefficient of carry of 0.5 and a coefficient of increase of 0.75, is 3×10^6 ft^3.

"Figure 29 gives the dimensions of the anchor piles. To calculate the stability one takes into account the most unfavorable conditions to be encountered through the horizontal and vertical components of the tension and, finally, the static, dynamic and thermic pressures of the ice.

"The boom itself is formed of two steel cables 1 inch in diameter, taking on a parabolic form under the effect of the pressure of the ice. The pressure is evaluated at 1000 lbs. per linear foot.

"The two cables are held together by 'U' bolts and wooden floats, in such a fashion that the upper part of the boom nearly coincides with the surface of the water.

"A safety mechanism permits the opening of the boom and lets pass the ice in case the pressures on the cables becomes greater than those used in the calculations.

"Every 2.5 feet have been installed spacers 4 ft. high to retain a relative thick accumulation of ice. This description is illustrated in fig. 30.

"The dike on the right bank is to control the floodings of land downstream. This dike was constructed with available material and its characteristics are shown in fig. 31."

"Figure 32 shows the backwater curves without ice, before and after the construction of the sill. These curves have been calculated considering a discharge of 7300 cfs."

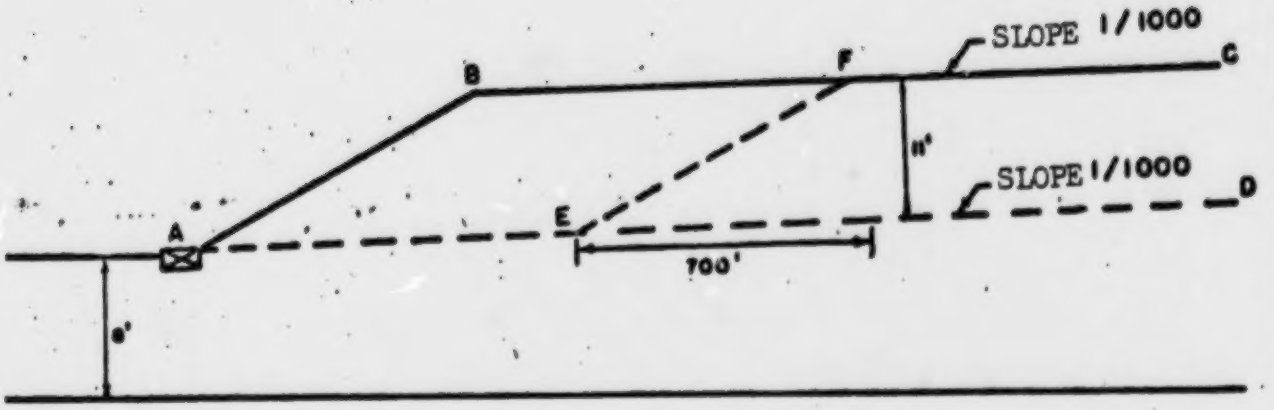

SLOPE 1/1000
B
F
C
11'
SLOPE 1/1000
D
A
E
700'
8'

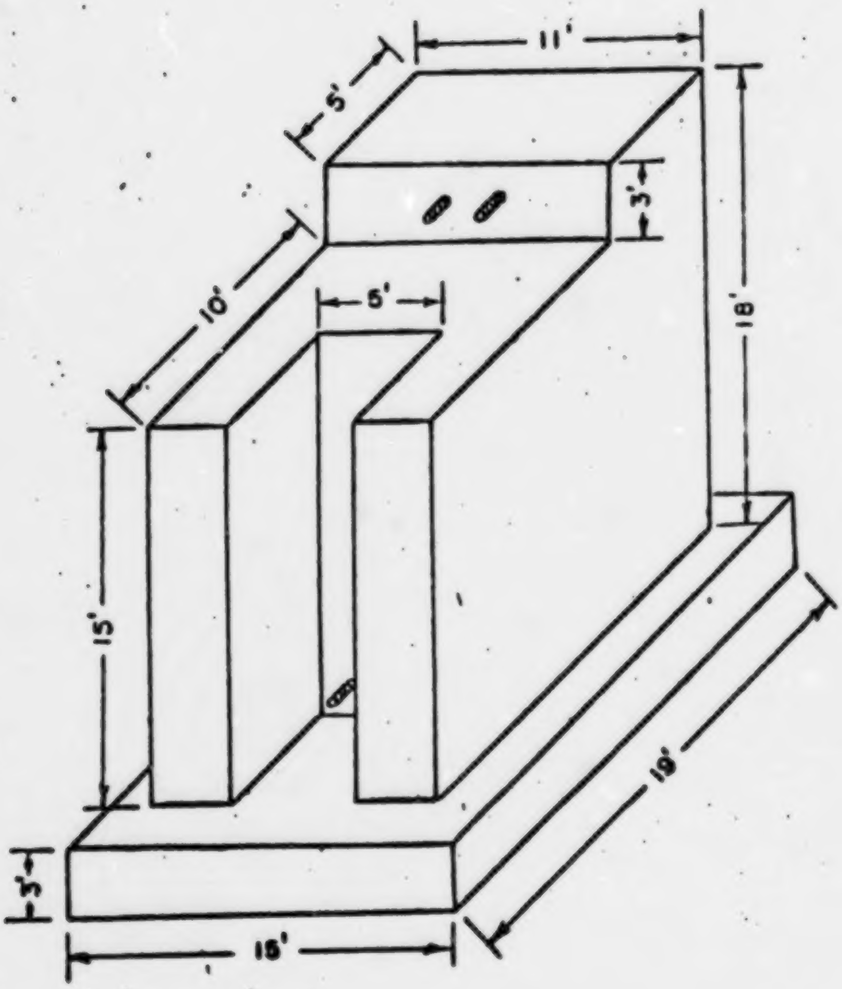
FIGURE **No. 28**

(Llamas, 1965)

FIGURE **No. 29**

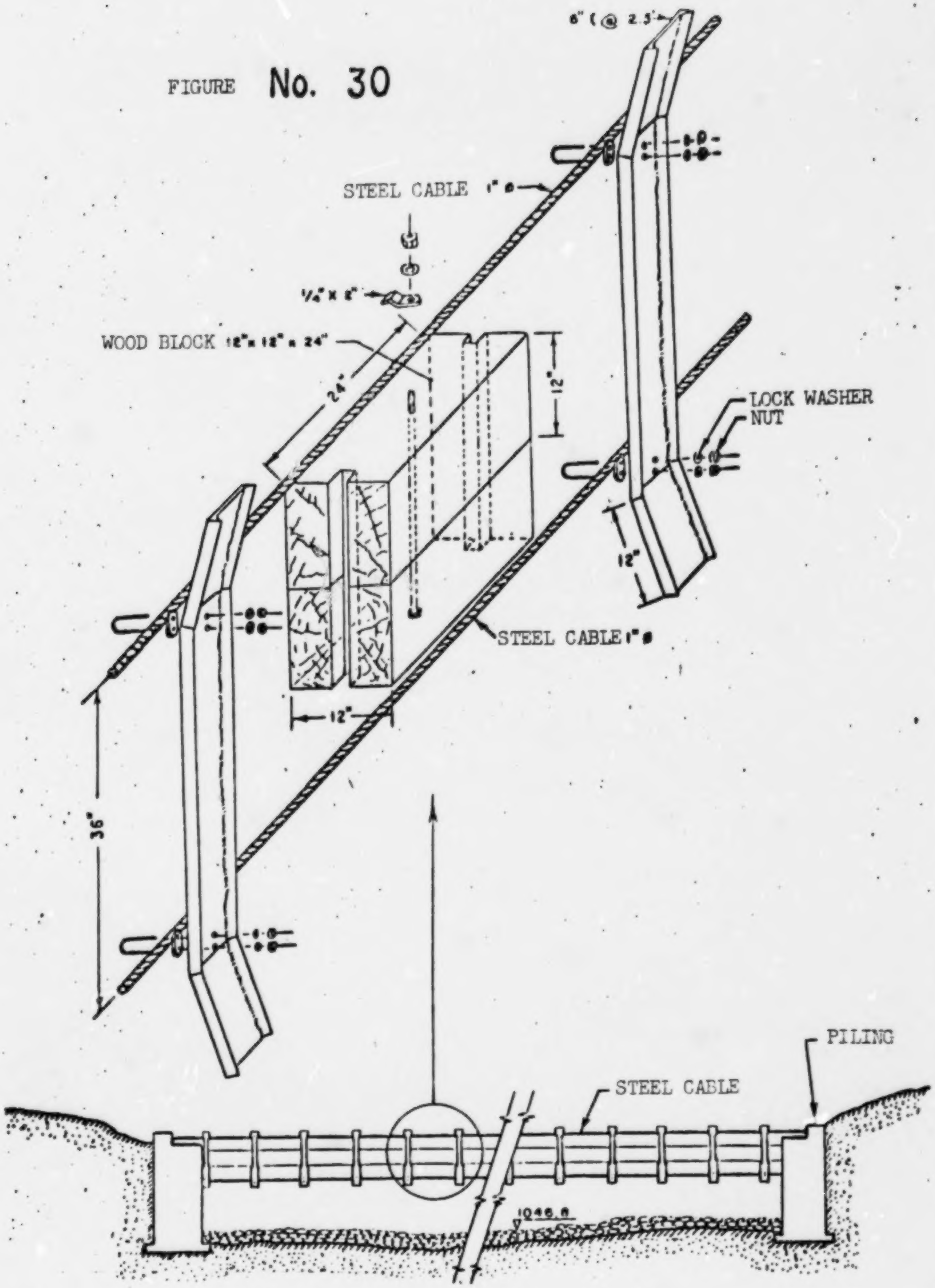
ICE BOOM AT DROLET

ANCHOR PILING

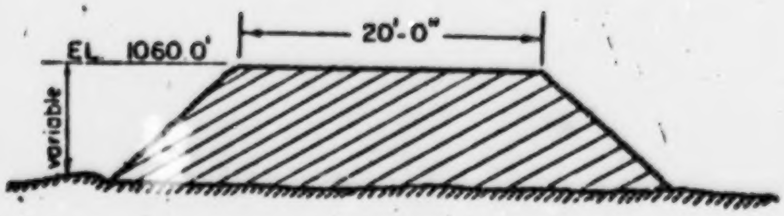

11'
5'
3'
10'
5'
18'
15'
19'
3'
15'

(Llamas, 1965)

FIGURE **No. 30**


6" [@ 2.5'
STEEL CABLE 1" ø
1/4" x 8"
WOOD BLOCK 12" x 12" x 24"
24"
12"
LOCK WASHER
NUT
12"
STEEL CABLE 1" ø
12"
36"
PILING
STEEL CABLE
1046.8

GENERAL VIEW OF THE ICE BOOM (Llamas, 1965)


EL. 1060.0'
20'-0"
variable

TYPICAL SECTION

FIGURE **No. 31**

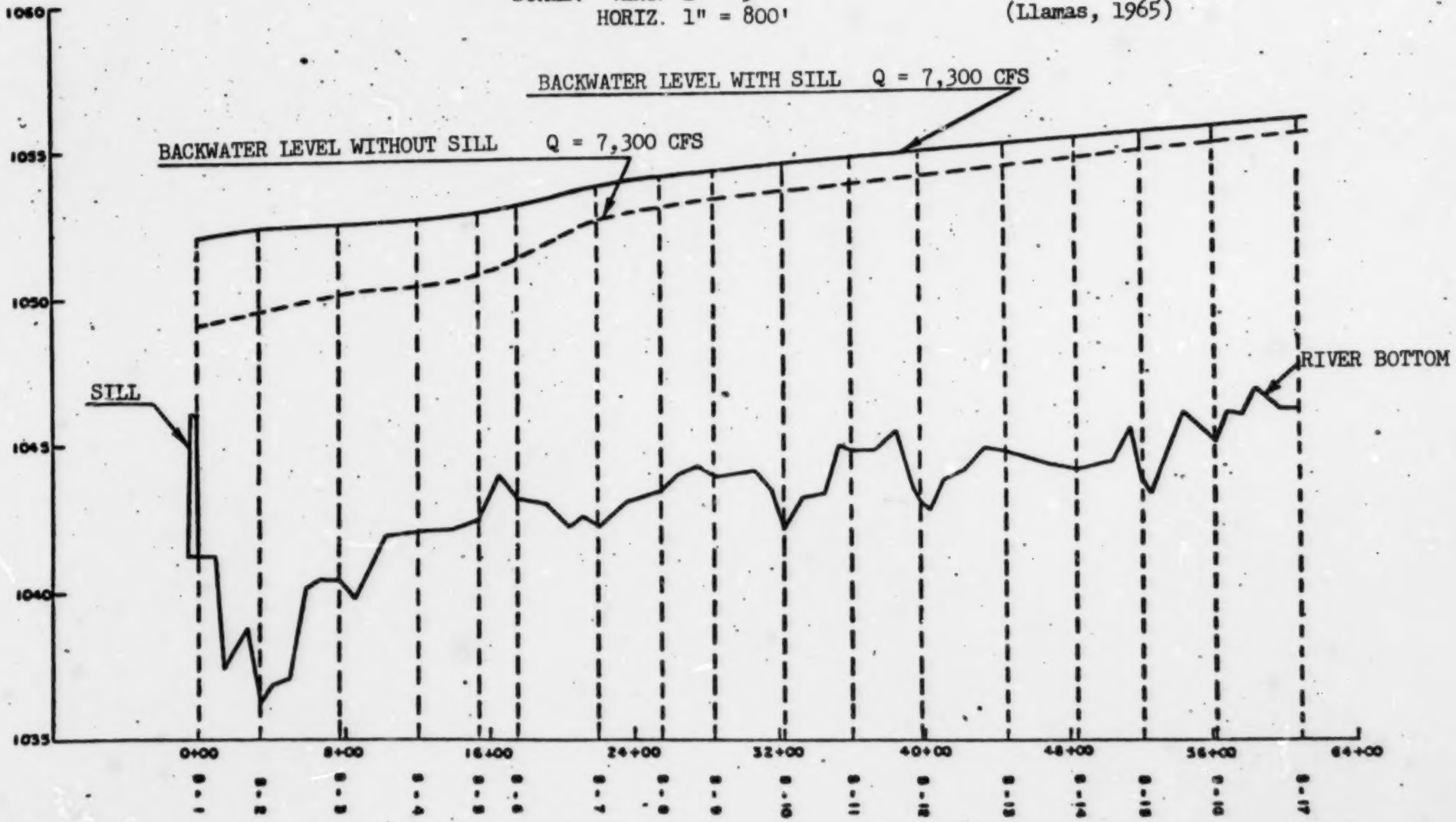
(Llamas, 1965)

FIGURE No. 32

LONGITUDINAL PROFILE

BACKWATER CURVES Q = 7,300 CFS
SCALE: VERT. 1" = 5'
HORIZ. 1" = 800'

(Llamas, 1965)



Michel (1967) describes a method of calculating wind effects on ice booms.

> "The problem of the distribution of the forces in the interior of an accumulation of ice bits of a constant thickness retained by a boom in a rectangular channel, is identical with that of a mass of grain in a silo having two dimensions and can be treated in the same manner. The important forces, which are similar to those of a weight of grain are, as shown in figure 1, the tangential forces exercised by the flow passing underneath, by the wind and finally, the component of weight in the inclined field.
>
> "A - General equilibrium of the restraints in the massif
>
> "This problem can be treated with the aid of a theory well verified by Caquot for silos, which assumes that the total pressure is transmitted by an action of an arch on the walls of the canal. By reason of the constant discharge, per unit surface, the system of arches consists of parabolic supports in the direction of the principle forces and toward the interior of mass.
>
> "By reason of this distribution, the reaction of infinitely long shores is given by:
>
> $$\tau B = 2 R \sin \psi \tag{1}$$
>
> Where:
>
> τ : the total tangential force upon the exterior.
>
> ψ : the angle of internal friction of the ice against the sides of the canal.
>
> "Consider, Figure 1, a transverse section of the ice field normal to an imaginary arch. The resistance which the field develops under the action of the principle force is:
>
> $$p_1 = \frac{(t - t_o)\,\gamma'\,(1 - \epsilon)}{K_\phi} = \frac{(\gamma - \gamma')(1 - \epsilon)t_o}{K_\phi}$$
>
> $$t\,\sigma_{n_1} = \frac{p_1\,t_o\,\gamma}{2\,\gamma'}$$
>
> "And the total action upon the shores becomes:
>
> $$R = \sigma_r\,t = \sigma_{n_1}\cos\psi\,K_\psi\,t = \tfrac{1}{2}\cos\psi\,\frac{K_\psi}{K_\phi}\,\frac{(\gamma - \gamma')\gamma}{\gamma'}\,(1 - \epsilon)\,t_o^2 \tag{2}$$

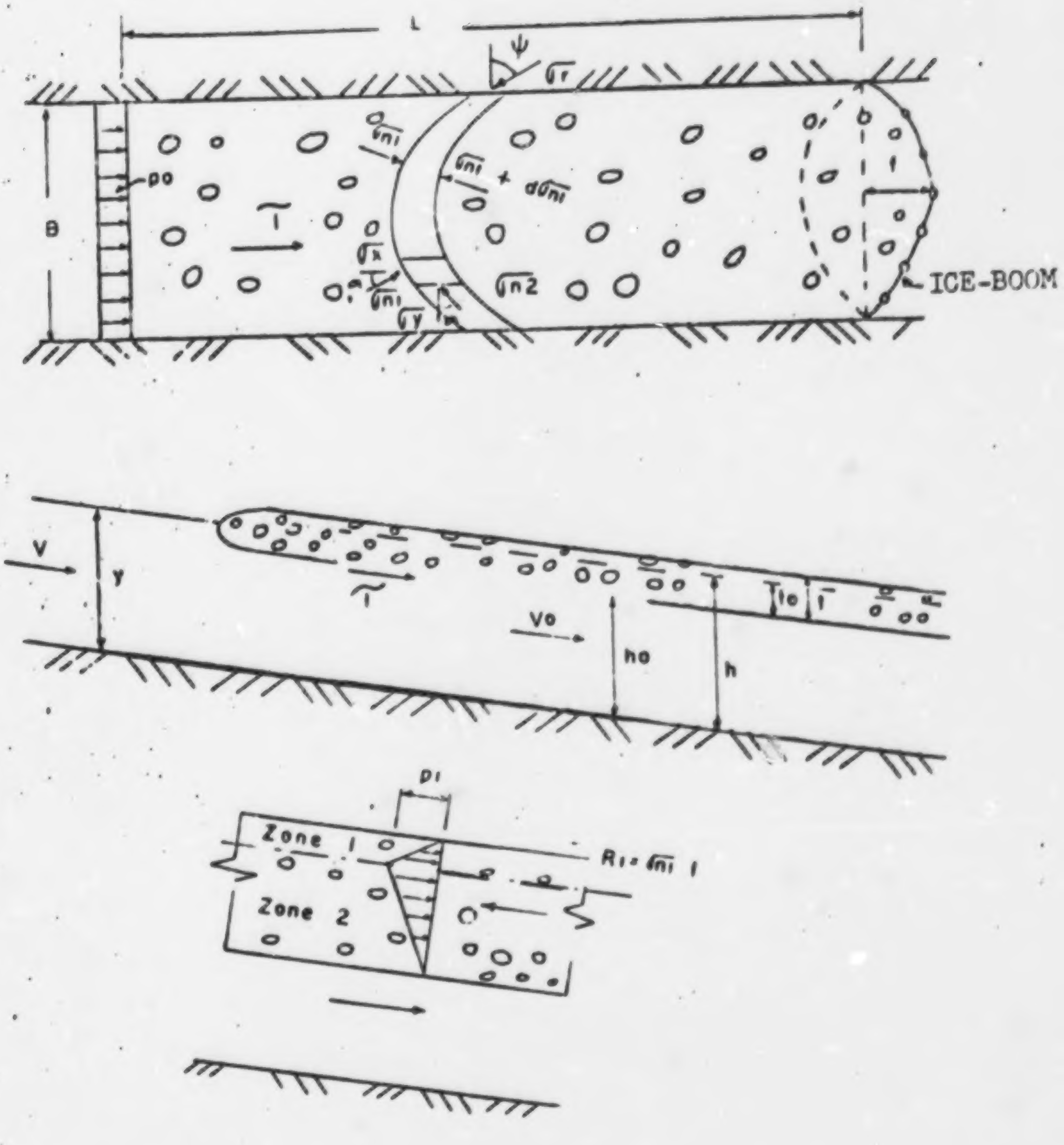

L
ψ
σr
σn1
σn1 + dσn1
po
B
τ
σx
σn1
σy
τm
σn2
ICE-BOOM
V
y
τ
Vo
ho
h
to
t
D1
Zone 1
Zone 2
R1 = σn1 t

FIGURE 1.

DISTRIBUTION OF FORCES WITHIN A BROKEN ICE FIELD (Michel, where $K\psi$ and $K\phi$ are respectively the active coefficient of resistance to the accumulation of the pressure toward the interior of the mass and that on the side.

"We have shown previously (Michel, 1965; Michel, 1965; Michel, 1966), that the maximum force T_∞ which can be transmitted to a boom is given, under these conditions of distribution of the forces by:

$$T_\infty = 3.6\,\tau\,B^2 \qquad (3)$$

"That is to say with (1) and (2):

$$T_\infty = 1.8\,\frac{\sin 2\psi\,K_\psi\,(\gamma - \gamma')\gamma}{K_\phi\,\gamma'}\,(1-\varepsilon)\,t_o^2\,B$$

The maximum value of T_∞ is obtained by:

$$\psi = \phi = 30^\circ$$

and ε minimum = 0.3

"This gives:

$$T_\infty = 6.25\,t_o^2\,B \qquad (4)$$

"B - Limitation of the hydraulic pressure

"There is a limit to the thickness of an ice field under the effect of the tangential restraint force caused by the flow. If the discharge is gradually increased under the accumulation of ice, the field thickens by successive additions until the increase of the hydraulic pressure, by reason of the reduction of the flow surface, becomes much greater than the resistance of the field to this pressure. The field becomes then unstable and passes under the boom....

"One can show (Michel, 1965) that this occurs when:

$$t_o/h = 0.4 \qquad (5)$$

"With the relation (4) one then obtains the maximum possible pressure of an ice field upon a boom, caused by a flow:

$$T_\infty = h^2\,B \qquad (6)$$

T_∞ will be the total pressure in pounds, h and b the depth and the width of the rectangular canal in feet.

"C - Influence of the effect of the wind

"The formula of Prandtl has been used with a certain success (Kennedy, 1958) for an identical problem in the case of a mass of pulpwood.

"In using this formula for a rugged turbulent flow established in a conduit only the tangential force exercised by the wind upon the surface of the field can be given:

$$\tau_a = \rho_a V^2/(5.75 \log y/K_e + 8.5)^2 \qquad (7)$$

where K_e is the roughness equivalent to the surface which can be taken equal to 1.5 feet or more and here the distance from the surface where the wind is measured, generally 33 feet.

"These values give:

$$\tau_a = 2 \times 10^{-5} V^2 \qquad (8)$$

where V is in miles/hour.

"In the case of an extreme wind for the calculation of 70 miles per hour, this restraint becomes:

$$\tau_a = 0.1 \text{ lbs/ft}^2 \qquad (9)$$

"With relation (3) one then finds that the maximum force exercised on the boom only under the effect of the wind is:

$$T_m = 0.36 B^2 \qquad (10)$$

"But an ice field can only thicken to $t_o = h$, the bottom of the canal then takes an important part of the load, which will not be transmitted to the boom. There is now another limit to the maximum force exercised by the wind on an ice boom:

$$T_m \leq 6.25 h^2 B \qquad (11)$$

"A numerical calculation clearly shows that in the majority of the cases the relations (10) and (11) are more strict than relation (4). The maximum force exercised by a field of ice bits upon a boom will be generally caused by the effect of a tempest wind on the field if the flow is very much reduced."

Livshits (1961) makes reference to Russian ice booms. Figure 29 shows a type of ice boom in place. The boom consists of wooden gratings (figure 30) 0.8 - 2.9 m wide and 4.5 - 6.5 m long, (with a peak attached to the down current edge) varying with the ice conditions. The gratings are spaced 0.5 m apart on hawsers (figure 29). The string of gratings is placed in the river. The length of the peak varies with the depth of the water, the current velocity and ice thickness.

One cable is sufficient to hold the boom in position as long as the strain is less than 45,000 Kg. Above that, several cables must be used. A table is supplied on the size of logs to be used under differing conditions of strain and channel size.

Relationships are also given between current velocity and hydrodynamic pressures in the presence of varying ice covers. These constants are used to determine cable diameters necessary for supporting the boom.

$$T_{max} = To \quad B:10 + T_{LP} (B:10)^2$$

where: T_{max} is the maximum cable strain

To is the water pressure

T_{LP} is the ice pressure

B is the stream width

Once constructed the grates of the boom are put across the river and the ends of the cables securely anchored in the banks.

To prevent the build up of great dynamic pressures on the boom, small charges of explosives are used to fracture the ice jam, or gorge, formed behind the boom during the ice drift. This would appear to be a continuing process.

Berdennikov (1964) discussed some features of ice booms in a preceding section of this report.

Two other Russian reports by Latyshenkov (1946) and Filimov (1948) discuss ice booms.

The unsuccessful use of an ice boom in France is reported by Siegfried (1957).

> "During the winter of 1899, pieces of chain were stretched across the Loire upstream from Nantes to prevent ice from drifting into the harbor. The chains instantly caused an ice jam. Ice did not drift into the port, but extensive flooding, upstream of the ice jam, caused considerable damage to the shore."

In an early account, Keefer (1898) describes a proposed ice boom below Lake St. Louis (St. Lawrence River) where jam conditions are apparently similar, but on a smaller scale, to those reported by Foulds (1967, 1964) in the Niagara River.

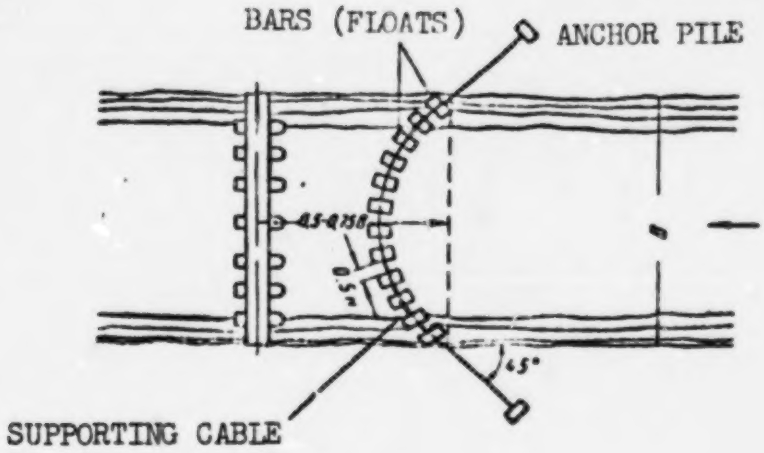
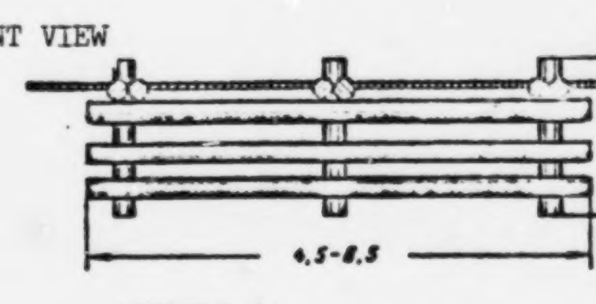

BARS (FLOATS)
ANCHOR PILE
0,5-0,75B
0,5 m
B
45°
SUPPORTING CABLE

FIGURE 29.
POSITION OF THE ICE-BOOM

a-SIDE VIEW


CABLES
PEAK
0,80-2,30
h
4,5-8,5

b-FRONT VIEW

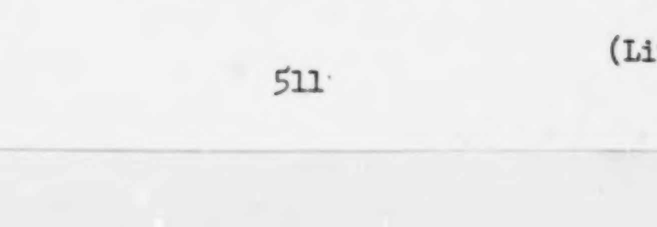

0,30-2,30
4,5-8,5

FIGURE 30.
FLOATING BARS (GRATES) OF THE ICE-BOOM

(Livshits, 1961)

"The Royal Commission of 1886 came to the conclusion that the only remedy for ice floods was by reducing the quantity of ice which descended below the Lachine Rapids by means of a boom supported by piers across the foot of Lake St. Louis.... This lake, after having been frozen over, sometimes breaks up in a winter thaw with an easterly gale, when all its ice may descend below; it also may, before it is closed in its channel, have its bordage ice broken off by wind and sea and sent below Montreal. The value of a boom in arresting floating ice and in causing ice to take in a current where freezing over would be delayed until the coldest weather, or not take place at all, has been proved by experience on the Ottawa River, where an ice bridge is formed by the lumbermen with the aid of a boom in positions where it could not otherwise be obtained."

Pariset, Hausser and Gagnon (1966) describe a study plan on an ice boom to be located in the Laprairie Basin (downstream from Lake St. Louis) near Montreal.

"The ice boom, consisting of a series of reinforced concrete piers spanned by heated steel beams adjusted to the water level, was erected some 2 miles above the upstream limit of Montreal Harbor, (Fig. 7).

"The main purpose of the boom is to help in the triggering of the formation of an ice cover on the Laprairie Basin (shown on the map) to reduce, early in winter, the free surface area and, consequently, the volume of ice produced in the basin and carried in the jams downstream. It must be noted that without a boom, a cover would form on the Laprairie Basin only after the maximum water levels had been reached in Montreal Harbor. With the boom, the major part of the ice in the Lachine Rapids, located upstream from the Basin, would also be trapped in the low velocities zone underneath the cover leaning on the structure."

Stothart and Croteau (1965) describe some results of the study by Pariset, Hausser and Gagnon (1966).

"A few structural details should be of interest:

"There are 72 piers and two abutments, stretching from Nun's Island on the Montreal side to the Seaway dyke on the south shore. The piers are just 88 feet on centres, with those in the free water channel area ... being just over 176 feet on centres....

"...The bottom elevation of the piers is set some five feet into the rock to ensure stability.

"In order to obtain rapid pier construction, their base is being completely encased by a metal caisson. The caissons, and hence the bottoms of the piers, vary from 16 to 20 feet in width and from 55 to 67 feet in depth of length. The concrete for the pier base is poured up to eight feet below the water level, using a fixed tremie method. The rest of the base and all of the pier are then poured in the dry, using conventional methods, up to a top elevation of 72 feet.

"The piers have a 4-foot recess on either side to receive the floating stoplogs which have overall dimensions of 6' x 5'7" x 82'1". They are built much in the same fashion as a ship. The ends of the logs will be equipped with guide rollers to transfer the thrust to the piers. The stoplogs will be trimmed, using concrete blocks as ballast in order to achieve, roughly, a four foot draft.

"To prevent ice from adhering to the logs, permitting their removal when required, they will be heated, using infra-red lamps placed on the service platform. The roller bearings are assured smooth functioning by separate heating of the notches in each pier. The whole structure will require power in the vicinity of 10,000 K V A.

"A pre-stressed concrete deck is mounted on the top of the piers to provide access to the logs and electrical equipment. Workshops will be built in the area to maintain and operate the equipment. Two trucks, mounting specially designed winches, will remove and replace the stoplogs for periodic maintenance and for storing on top of the piers during summer months....

"Selection of the actual dam site was limited by the geography of the region of two areas:

a. the lower section of Lake St. Louis; or

b. the lower section of Laprairie Basin.

At one time, we considered a dam on Laprairie and a separate boom on Lake St. Louis. It was decided to settle on a spot about 1,000 feet upstream from the Champlain Bridge and, hence, realize the storage capacity of practically the whole Laprairie Basin....

"Extensive soil borings, model tests, and hydraulic studies followed. The model work was done at the LaSalle Hydraulic Laboratory. As usual, calibration to give similar characteristics to the prototype was difficult under the following variety of scales:

Vertical	1:150
Horizontal	1:600
Volumes	1:54,000,000
Velocities	1:12.25
Liquid Flow	1:1,102,000
Slopes	1:4
Ice Flow	1:137,500
Forces	1:13,500,000

"The model covered about eight miles of the river. 'Ice was simulated', using polythene cubes, three to four millimeters base and height. They were fed into the model using separate funnels and control valves....

"I am going to review some seven specific points...associated with construction and operation of the Control Dam.

"1. What is the minimum water level or reduced velocity at which ice will form in the Laprairie Basin?

"This was found to be Elevation 35. In the past this level was only reached after the ice cover had progressed upstream to the Montreal Harbour proper. Since, under ideal ice making conditions, it takes about one week to cover the 2-1/2 mile area between the harbour and the dam, we will be able to provoke a cover about a week earlier than usual.

"2. What total amount of ice can be stored in Laprairie Basin?

"...Formulas relating the rate of ice production to the free area of water and the temperature difference between air and water have been evolved. In the model, ice production varied from 250 c.f.s. to 750 c.f.s., being equivalent to air temperatures of about 26° F. and 12°F. respectively. Ice storing below Elevation 35 was considered nil. For levels about 35, the sheet progresses upstream until it reaches the foot of Lachine Rapids, when it starts to flow under the existing sheet, partially forming dams, and a portion continuing downriver with the water level rise until it reaches the control structure. The ice will flow under the stoplogs, and an equilibrium is then reached where the new ice coming down equals the amount going under the logs. Elevation 44 is suggested as the maximum water level to be expected and, at that level, the stored ice quantity varied between 1.5 x 10^9 cu. ft. and 2.5 x 10^9 cu. ft....

"3. What other effects would the structure have on the water levels in Montreal Harbour and vicinity?

"They found only better control of all ice conditions causing extreme levels, including flash releases of ice and run-off through a somewhat controlled waterway in the spring.

"4. What effects would a large release of ice from Lake St. Louis have when an ice cover existed on Laprairie?

"...A mass of ice would probably ground prior to building up against the existing cover. This happens since the water level downstream remains somewhat stable, having no cause to rise. This, of course, helped us to conclude that a separate ice boom on Lake St. Louis was not necessary.

"5. What ice thrusts should be expected against the stoplogs and piers?

"...On the model, thrusts were evaluated at different water levels, using a suspended piece of wood resting against detector bands which were wired to a Sandborn recording gauge. Maximum recordings were reached just before the ice grounded. Theoretically, the works of Mr. Edwin Rose, in a 1946 A.S.C.E. publication, and also Timishenko's and Bryan's theory of thin plates were considered. These involved viewing the ice sheet as a thin plate, and taking into account the effects of wind and forces developed by the expansion of the ice sheet under solar radiation.

"In the final analysis, the piers were designed to resist a maximum load of 10 kips per lineal foot of structure -- the other elements, a design load of 5 kips per foot.

"6. Where should a free water channel be located to assist the ice run-off?

"This was found in the vicinity of Pier 15, but in order to use the maximum depths of the river, the actual evacuating channel was moved out a little further and fixed between Piers 19 and 22.

"7. What draft should obtain for the stoplogs?

"The model indicated that a draft of more than four to six feet for the stoplogs would not improve the functioning of the control structure."

No field results on the effectiveness of the structure are given. However, subsequent informal field reports indicate that three gates of the structure were swept away in early February by a large 20 inch thick floe.

Stevens (1940) describes the effect of a reservoir on river ice retention.

"Apart from an increase in winter flow, the effect of a reservoir in such a stream is first to diminish the quantity of ice below it. For example, consider a turbulent river, 100 miles in length, with a valley at the lower end. In its natural condition the river pours into this valley all the ice formed throughout its length.

"Now, if a substantial reservoir is built 25 miles above the valley, it will constitute an ice-barrier for the 75 miles of river above it, since no frazil ice can pass the reservoir.

"Moreover, the water from this reservoir is slightly above freezing temperature and frazil ice cannot form until the water has been cooled to freezing in the channel below. It is obvious, therefore, that after the construction of the reservoir the quantity of ice reaching the valley will be limited to that formed in the lower 15 or 20 miles of river, whereas, prior thereto, 100 miles of river contributed its ice to the valley.

"The first effect of increasing the flow is to diminish the quantity of anchor-ice that may form, due to the increased depth of water reducing the quantity of heat that may be radiated directly from the bed of the stream.

"The second effect is to diminish the turbulency and encourage the tendency of the water, at freezing temperature, to remain on the surface. Thus, the formation of frazil ice is more likely to be confined to the surface of the moving water, which is not the case when the water is brought to a uniform freezing temperature by thorough mixing.

"The third effect is to increase the quantity of frazil ice about in proportion to the increase in the area of the water-surface.

"The fourth effect is to increase greatly the transporting power of the current, thus enabling the river better to carry its icy load without gorging and, therefore, delay the formation of the gorge until a rise of temperature destroys the tendency of the ice to gorge. The increase flow tends to cut out the gorge quicker with a slight rise in temperature; in other words, the river becomes more sensitive to the temperature-changes and the duration of the overflow is less than with the normal flow."

The artificial construction of natural ice bridges is suggested by Kanavins (1944). The purpose is to group ice where artificial jamming is harmless. Kanavins studies were conducted to find a method of reducing ice jam problems at a newly constructed power plant.

"The formation of the ice cover in the swift water section of the Dvina has been closely observed since 1928. These observations led to the idea of creating ice heads, such as those which normally form at the beginning of winter in the Riga Harbour district and the Keggum artificial lake above Friedrichstadt, at the lower end of the larger rapids which did not freeze over. The purpose behind this idea was to halt the drift ice masses coming down from the rapids, to employ them to dam up the water, and thus partially or completely to cover the rapids themselves with the obstruction, and promote the formation of an ice cover in the stretches of the river which were influenced by the obstruction. In this manner the further formation of the depth ice in the rapids would be reduced considerably, or might possibly be eliminated altogether, even in autumn, due to the artificially produced freezing. For this purpose the following means were employed: ... 1) border-ice bridges; 2) drift ice dams; 3) artificial production of depth ice.

"a) Border-ice bridges

"A border-ice bridge consists of a section sawed out of the border ice and placed diagonally across the river.... The masses of drift ice coming down from the upper reaches of the river are halted by this artificial barrier and freeze together under severe frost conditions. Since the process of depth ice formation is normally most intense during autumn the ice bridges were begun immediately after the frost set in.

"The locations chosen for these operations were points immediately below the rapids where the flow of the river is quiet and the bed is deep.

At these points the required building material, the border ice, is at its widest and firmest. It is also desirable to have a bend in the river at the location of the bridge, since the possibility of obtaining a favourable transmission of the pressure of the current from the bridge to the shore is thus provided....

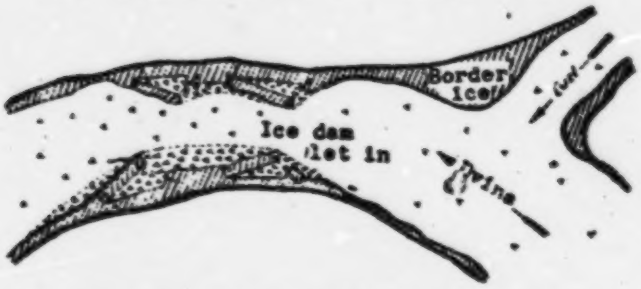
"The strip of border ice should be chosen at the place where the flow of open water is narrowest and on the side from which it is easiest to get the strip into place across the river with the aid of the current. Especially important is the forming of the foot of the ice bridge. The angle of inclination of the foot, α , should be chosen such that the bridge may not slide off. Friction in the direction of midstream must not be allowed, and it is also undesirable in the shoreward direction. The length, L, of the bridge should be chosen between the limits 1 and 1.4 b, where b is the span of the open water in the river. Normally L will be equal to 1.2 b for the slope of the supports $\tan \alpha = 2.5$. In practice the ice bridge strip may be as long as 250 metres, i.e., the space to be bridged may be as much as 200 metres wide. Longer sections than this will not withstand the bending stress and will break. The width chosen will depend on the thickness and strength of the border ice. It is undesirable to have the strip too wide.

"Often it proved necessary to strengthen the foot of the bridge or the ice strip itself. This can be done by freezing wires into the ice, a process which results in something akin to reinforced concrete....

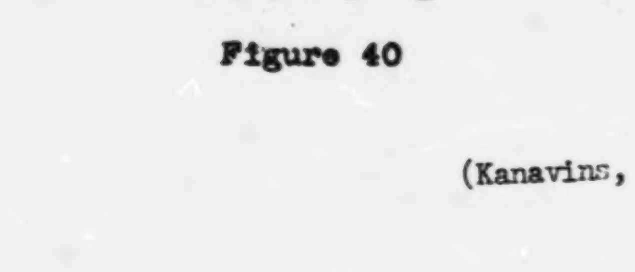
"During early autumn...the border ice is still too narrow and weak. Before the bridge is erected, therefore, it should be artificially expanded and strengthened. The method by which the border ice is artificially expanded is shown in Figure 40.

"By means of such bridges one of the largest rapids of the Dvina, the so-called Priedulajs Rapids at Stockmannshof, between 151 and 154 km. from the mouth, was covered with surface ice in the autumn of 1941.... In a few days the bed of the river beneath the solidly frozen top layer at the bridge was completely clogged with depth ice to a depth of 10 metres. When the quantity of ice was measured on the 15 December it was found that approximately 150,000 cu. m. of sticky depth ice had already collected in the 200 metre stretch of the river. The water of the Dvina continued to flow only through single, hollowed-out channels near the shore. The water level had risen two metres and the entire lower end of the Priedulajs Rapids was already under the influence of the dam. Near the dam the border ice had expanded rapidly and the necessary conditions for freezing over became more and more favourable, until practically the whole rapids were covered with a solid ice cover by the 16 January....

Artificial extension of the border ice at Stockmannshof in the Winter of 1941-42.


Border ice
Ice dam let in
Dvina

Artificial bridging at Stockmannshof in Winter of 1941-42.


Border ice
Dvina

Scale 1:5000

Figure 40

(Kanavins, 1944)

"Later, similar ice bridges were constructed downstream on stretches of the river which were not frozen over, and by February the entire swift water section had a solid ice cover....

"b) Drift ice dams

"... It did not prove possible, by means of border-ice bridges, to limit the formation of depth ice on the second largest rapid of the Dvina, the Stutschka Canyon, nor ... above it, the three kilometer long Kahklis Rapids (from 135 to 138 km. above the mouth). On this stretch of the river the border ice, because of the swift current, was too thin, and its artificial expansion was prevented by the steepness of the banks....

"This method is based on the following scheme (Fig. 42): Use is made of the fact that the main current of the river, bearing the larger masses of drift ice, proceeds in zig-zag fashion down the bed of the river, now approaching one bank, now the other. A rake, fifty metres in length, constructed of poles, is placed diagonally in the current at a place where it approaches the shore and is anchored to the shore by means of wire.... The rake retains part of the drift ice, which due to the effect of the frost soon freezes and produces an arc-shaped border of ice. The pressure of the current is soon transferred from the rake to the shore, and when this occurs the rake has served its purpose. The arc-shaped border of ice, in its turn, deflects the current sharply towards the opposite shore. When similar rakes of poles are introduced into the river from the opposite shore it is found possible, under favourable conditions, to create a funnel shaped narrows at a place approximately 280 m. wide, at which the masses of drift ice soon pile up and come to a halt....

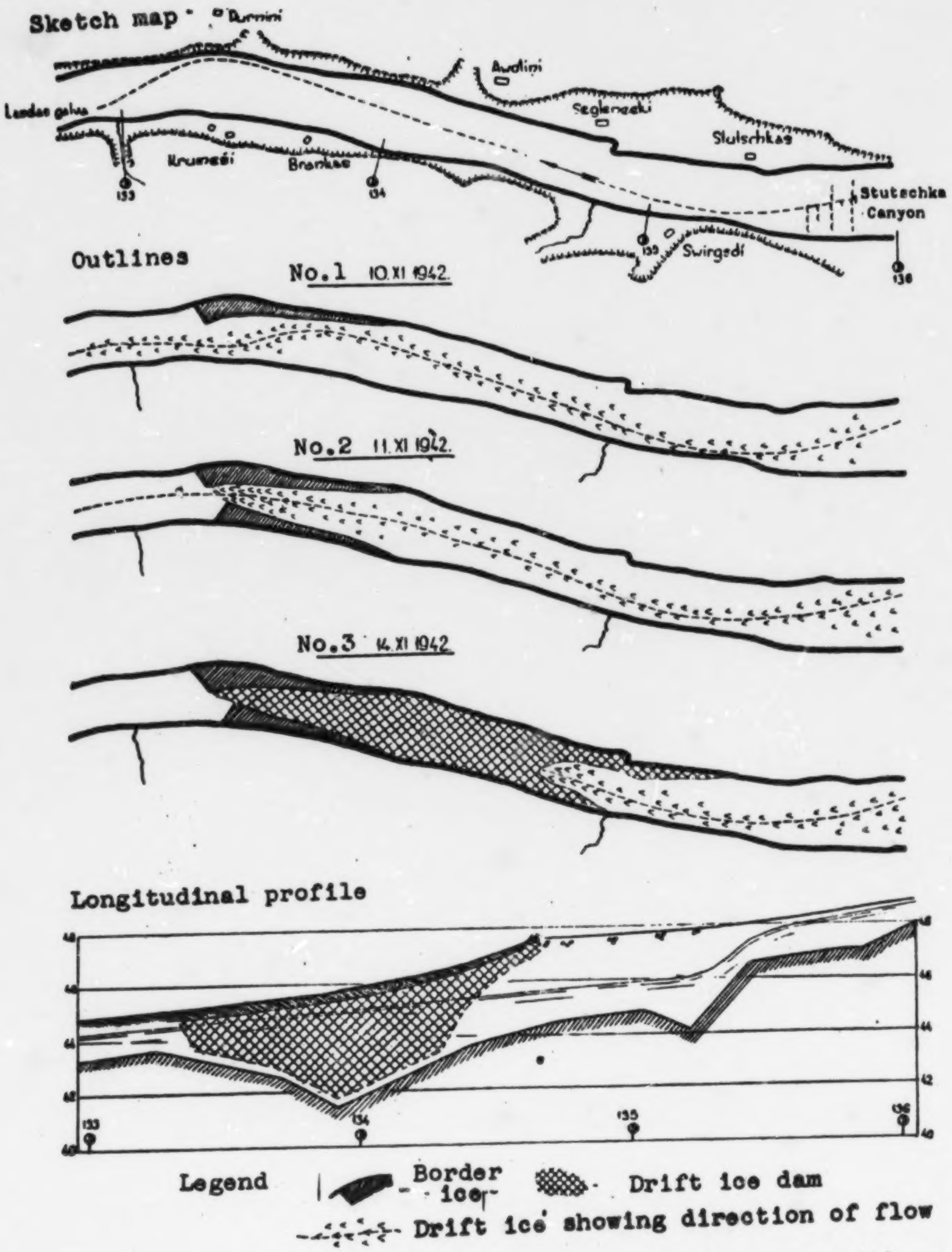
"Using this method of obstruction all drift ice masses coming from the rapids were halted within four days at the Purnin Bend (135 km. above the mouth) in the early autumn under moderate frost conditions down to -10° C. This created a dam of ice which extended for approximately 1.5 km. The changes in the river gradient at various times during the winter of 1942-43 are represented in Figure 44. As the sketch shows, within approximately one month one of the largest rapids of the Dvina was covered with ice, step by step, following frequent changes in the position of the ice masses with increases in the water level of from 1.0 to 1.6 metres. This is a section of the river which otherwise never freezes over, even during the severest winters."

"c) Artificial production of depth ice

"... Various methods of artificial depth-ice production were also used during the winter as a means of reducing the depth ice or forming an ice cover on the rapids.

Figure 42

THE DVINA AT SEGLENEEKI
Artificial ice damming


Sketch map
Dumini
Audlini
Lendas galus
Segleneeki
Stutschkas
Krumaši
Brankas
133
134
135
136
Stutschka Canyon
Swirgsdi
Outlines
No.1 10.XI 1942.
No.2 11.XI 1942.
No.3 14.XI 1942.
Longitudinal profile
48
46
44
42
40
133
134
135
136
Legend
Border ice
Drift ice dam
Drift ice showing direction of flow

(Kanavins, 1944)

DISTRIBUTION OF TOST MASSES AND VARIATION DUE TO ARTIFICIAL ICE BRIDGING ON THE DVINA AT PURNIN BEND (133 km. above the mouth) IN THE WINTER OF 1942-43. (Kanavins, 1944)

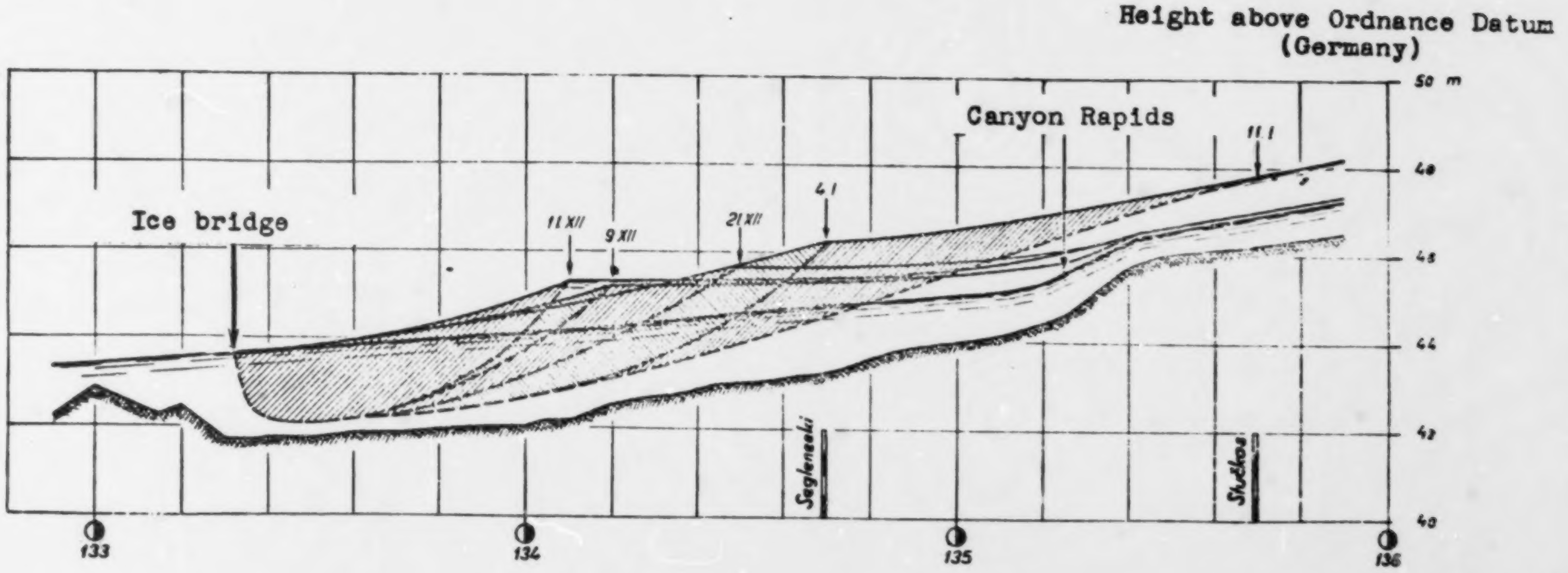


Figure 44.

"As already mentioned, from the research into the thermal and dynamic conditions underlying the formation of depth ice, ways and means were found of artificially promoting the formation of depth ice at any desired place in the rapids. This method was now used in order to promote the freezing over of narrow but very turbulent places. Experiments of this type were carried out at the Stockmannshof Canyon (150 km. above the mouth). Almost the entire boiling canyon rapid was covered with formations of depth ice, leaving only narrow cracks through which the water bubbled down. Light wooden poles were thrust at close intervals into the five metre per second current so that they reached the bottom, which was already covered with ground ice. Because of the artificially produced vortices the wooden poles were soon covered with soft, sticky depth ice down to a depth of approximately 50 cm. Under favourable conditions the test surface froze over artificially within a few days. The current flowed over the lower part of the ice cover....

"Another method was employed in places which are similar, but where the bed of the river is deeper. A depth ice floe was produced artificially on an open stretch of the river above the place where the stream narrows ... and was brought down into this narrow place. In this manner it is comparatively easy to produce a covering of ice over places which normally hardly ever freeze over. Experiments of this nature were carried out in the winter of 1941-42 in the Priedulajs Rapids district with the result that the formation of the ice cover on the unfrozen stretches of the river was considerably enhanced.

"It is difficult to lay down general principles regarding the method which may be most advantageously employed at any given place. The choice of the method must be determined by the conditions at the place in question. It is necessary first to investigate thoroughly the character of the river bed and the current, to determine the weather conditions and the character of the border ice, to discover the location of underwater springs, etc., before any conclusion may be reached regarding the employment of this or that method. Very advantageous combinations of the different methods are also possible.

"Corresponding variants of each of the methods described may also be adapted to the given circumstances. Border-ice bridges, for example, may be constructed by letting the border ice into the river from both sides. This is an advantage if the ice bridges are to be erected at a relatively straight section of the river. With these ice bridges the pressure of the current is distributed over two foot-supports. The border ice strips themselves in this case are much shorter and therefore much more able to resist damage.

"The drift ice dams have considerable advantages over the border-ice bridges. In the first place it is possible to put the wooden rakes in the river during the first frosty days so that the formation of depth ice is interrupted from the very beginning, whereas for the ice bridges the border ice must first be produced artificially. Secondly, the drift ice dams are more advantageous with respect to position."

Kanavins continues by describing grouping the "depth ice" in favorable river sections.

"As already mentioned, since the completion of the power plant at Keggum the main masses of depth ice coming from the rapids of the Dvina usually gather at the upper end of the artificial lake and further upstream on the section from Rikas to Aiselkschni (125 km. from the mouth). Packed together in dense masses beneath the ice cover, and here and there stopping up as much as eighty per cent of the river bed cross-section, these masses, because of their toughness and adhesive qualities, form an actual wall which the river is no longer able to overcome. Every year, during the breakup these masses create serious difficulties. It is known from observation and experience that the larger and softer the masses of depth ice are, i.e., the more water-tight, the more slowly they will disintegrate during the break-up, and the greater the flood will be.... Usually at the very beginning of the break-up an ice jam forms at the neck of the Keggum artificial lake and advances with a wave of water which may be as high as 10 metres, and drives into the solid ice cover.... The ice jam grows constantly in size as additional masses of ice come down from the upper waters of the Dvina, and the danger of flooding increases."

"To improve the situation in the spring during the break-up period, means were sought of obtaining a more favourable grouping of the depth ice in the swift-water section of the Dvina. This was accomplished by means of the ice bridges....

"When the measurements of ice quantities were made in the swift-water section of the Dvina it was found, surprisingly, that the masses of depth ice had grouped themselves principally at the five artificially erected ice bridges. The locations of the ice bridges, or dams, are shown schematically in the sketch diagram, Figure 50, together with the quantities of ice, their distribution and the groupings of the masses of ice."

"The important point is, however, that only a part of the damned up masses of ice moved (in the spring), the ice of the artificial bridge at Stockmannshof and of the obstruction at Purnin Bend opening a crack in the centre of the river only 50 m. across. The rest of the ice remained in the places where it had been packed together in high bars, in shallows, and on the shore, and disintegrated gradually on the spot....

"As a rough estimate, only about half the masses of ice from the swift water section of the Dvina reached Lake Keggum and even these were considerably ground up by dynamic forces during their progress through the rapids. The course of the break-up is schematically represented in the sketch, Figure 54."

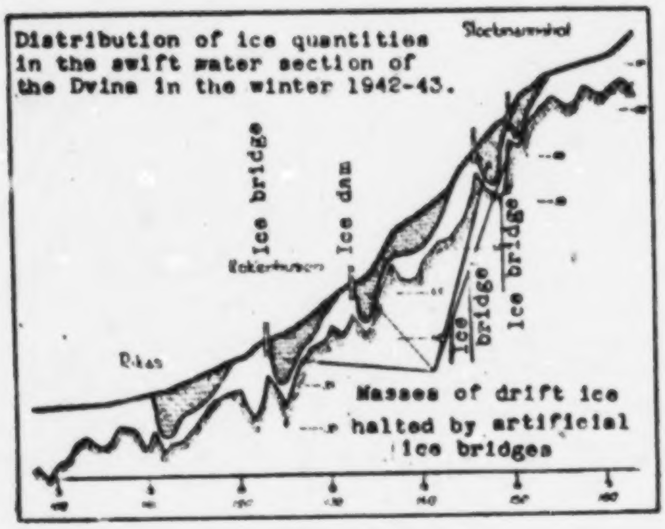


Figure 50

(Kanavins, 1944)

COURSE OF THE BREAK UP IN THE SWIFT WATER SECTION OF THE DVINA ON THE JAKOBSTADT-ASCHERADEN STRETCH IN THE SPRING OF 1943

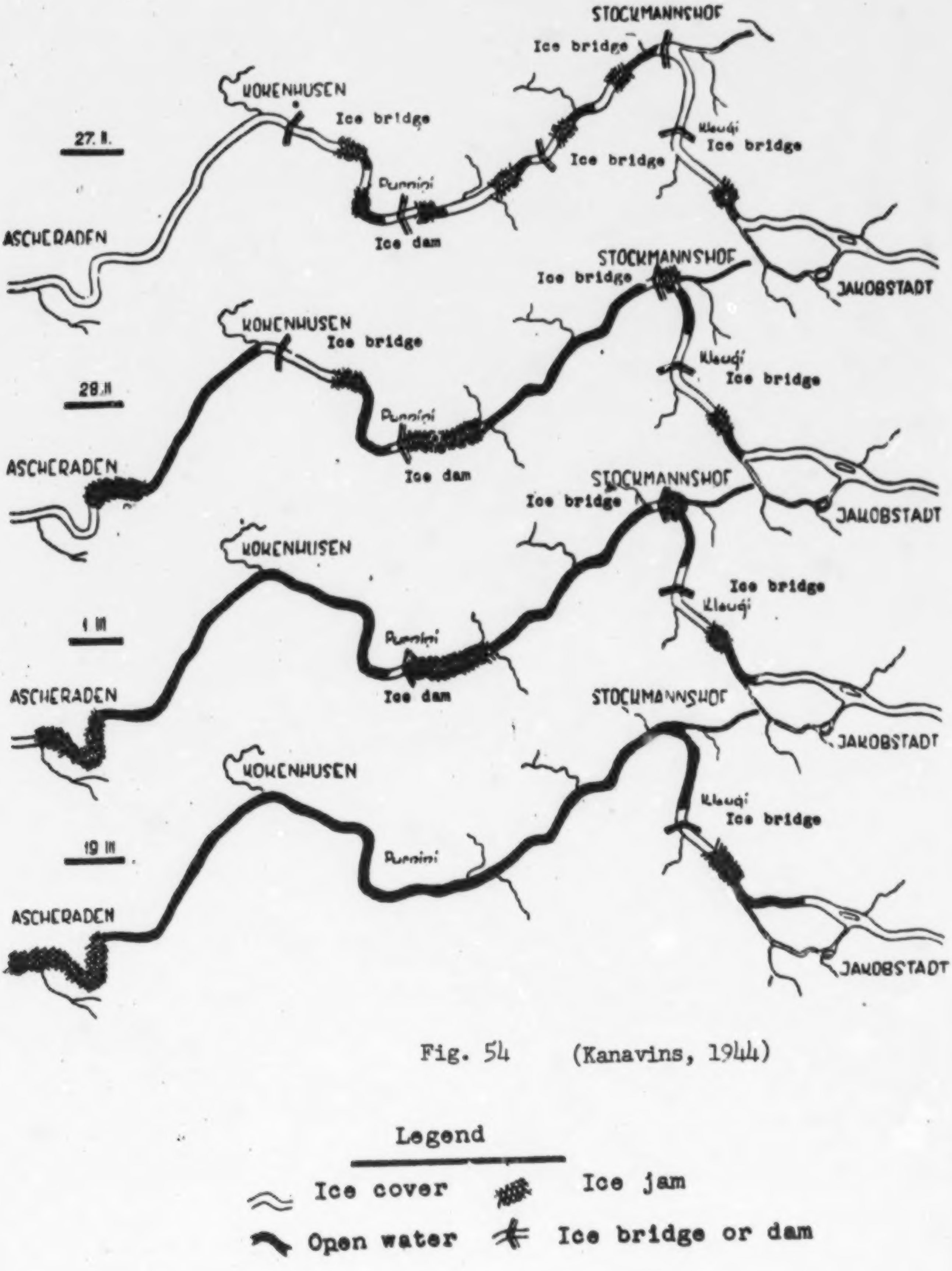

27.II
STOCKMANNSHOF
Ice bridge
KOKENHUSEN
Ice bridge
Klauģi
Ice bridge
Ice bridge
Punnini
ASCHERADEN
Ice dam
JAKOBSTADT
28.II
STOCKMANNSHOF
Ice bridge
KOKENHUSEN
Ice bridge
Klauģi
Ice bridge
Punnini
ASCHERADEN
Ice dam
JAKOBSTADT
1.III
STOCKMANNSHOF
Ice bridge
KOKENHUSEN
Ice bridge
Klauģi
Punnini
ASCHERADEN
Ice dam
JAKOBSTADT
19.III
STOCKMANNSHOF
KOKENHUSEN
Klauģi
Ice bridge
Punnini
ASCHERADEN
JAKOBSTADT

Fig. 54 (Kanavins, 1944)

Legend

≈ Ice cover ▨ Ice jam

━ Open water ╪ Ice bridge or dam

Stakle (1936) describes a system of accumulating drift-ice to bridge rivers. It is interesting that the methods are similar to those described by Kanavins (1944) and referred to as border-ice bridges. Stakle reports that attempts are made to "bridge the river by means of an artificial ice cover: shore-ice is chopped off on both banks and pushed into the stream: if the blocks of shore-ice are sufficiently long, an arch-like ice bridge is formed....

> "It happens at times that ice bridges constructed artificially from shore-ice are unable to withstand the mass of drift-ice."

Artificial damming using natural ice on the Neva River below Ivanovisk is described by Sovetov (1938). No details are given except that the dams were constructed from shore ice and that they were "definitely of benefit". The dams were used primarily to reduce the formation of frazil by providing the artificial cover.

Assur and Frankenstein (1963) recommended grouping river ice at a favorable location to eliminate ice jams at the confluence of the Mohawk and Connecticut Rivers in upper New Hampshire.

> "By far the most effective solution would be an earth dam ... with a concrete spillway designed in such a way that the spring flood waters would be discharged through the opening but the ice retained behind in a flooded area." The proposed dam location was upstream from the principle jam area.

> A wide meadow above the dam was to be used as a reservoir "for the accumulation and gradual wastage of ice. The dam would lose a considerable portion of its effectiveness if the meadow would not be flooded."

Groat (1920) describes some ice diversion structures on the St. Lawrence River at Massena. In order to obtain the full value of the paper, it is necessary to include a description of the river at the time of his investigation.

> "At the head of Croil Island the St. Lawrence River divides into the North and South Channels of the Long Sault Rapids. At the foot of Croil Island (see fig. 2) a large portion of the water in the South Channel returns to the North Channel down the Big Sny Channel between Croil Island and Delaney Island. At the foot of Long Sault Island nearly all the water in the North Channel returns to the channel south of Barnhart Island....
>
> "The water north of Sheek Island is an overflow from the Cornwall Canal, the surface of the water in which is about 25 ft. higher than the surface of the water in the river at the head of Barnhart Island....

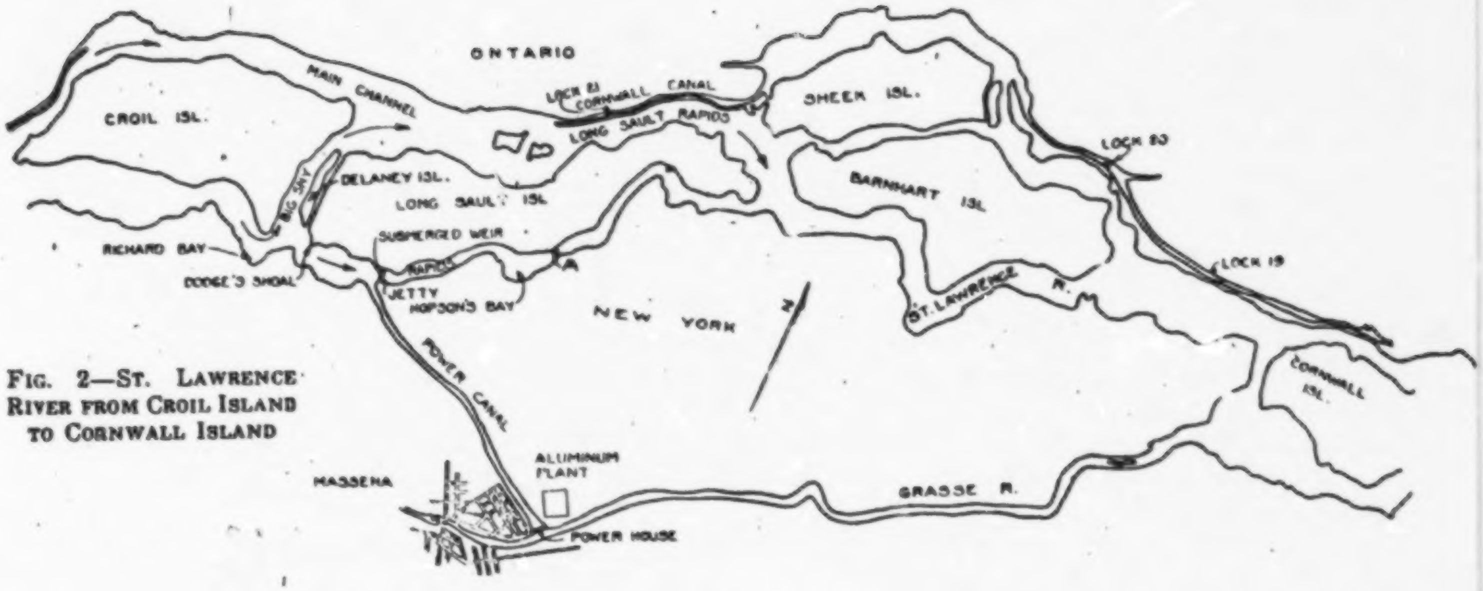

ONTARIO
MAIN CHANNEL
CROIL ISL.
LOCK 21
CORNWALL CANAL
LONG SAULT RAPIDS
SHEEK ISL.
LOCK 20
BIG SNY
DELANEY ISL.
LONG SAULT ISL
BARNHART ISL
RICHARD BAY
DODGE'S SHOAL
SUBMERGED WEIR
RAPIDS
A
JETTY
HOPSON'S BAY
NEW YORK
N
ST. LAWRENCE R.
LOCK 19
CORNWALL ISL.
POWER CANAL
ALUMINUM PLANT
MASSENA
GRASSE R.
POWER HOUSE

FIG. 2—ST. LAWRENCE RIVER FROM CROIL ISLAND TO CORNWALL ISLAND

(Groat, 1920)

"In the South Channel, above Dodge's Shoal, the water is several feet higher than it is at the head of Cornwall Canal (Lock 21), owing to the fact that there is a steep slope and rapid water down the Big Sny. There is rapid water at many points along the South Channel from the rapids over Dodge's Shoal to the foot of Long Sault Island, but the total fall will scarcely reach 30 ft. under the most favorable normal conditions of river and channels.

"The Massena power canal takes its water supply from the South Channel, about 4,000 ft. below Dodge's Shoal, being assisted by the submerged weir and jetty extending from the main shore to Long Sault Island...."

"There were two serious causes for these ice troubles. First, river ice was drawn into the canal in such large quantities, during heavy runs of ice, that the canal became jammed and choked until the water supply was practically cut off. Second, jams formed down river ... at the outlet of Hopson's Bay, in the South Sault Channel (see fig. 2).

"The jams which form down river build back upstream annually, causing high backwater at the foot of Grasse River. This backwater extends to the power house at Massena, thus reducing the head on the turbines during such periods, sometimes by as much as 10 ft. Upon further accumulation the jam extends back to the foot of the Long Sault, sometimes completely submerging and obliterating the rapids.... The jam then may continue up to the South Sault to Dodge's Shoal and there completely cut off the supply of water to the South Sault and consequently to the powerhouse.

The jams which form at the outlet of Hopson's Bay also build back to Dodge's Shoal in the same manner and cut off the water supply to the South Sault channel and powerhouse. A jam at any point further down the river may cause similar difficulties.

"Where the jams start

"The principal cause of obstruction was the jamming of the power canal with river ice drawn under the power company's boom across the canal intake. Tests on models, as well as actual experience, show that if ice lodges in sufficient quantity against a boom in deep water having considerable velocity, all ice subsequently drawn to the boom will pass under. Troubles with frazil ice forming on the racks at the powerhouse were of secondary importance, though embarrassing at times. It is the object of the ice diversion works to prevent the entrance of all kinds of river ice into the power canal.

"It would seem that there must be a number of causes which precipitate ice jams; but very frequently the causes popularly advanced are either very obscure or entirely incorrect. In the case of Lake St. Francis, for example, it seems to be commonly supposed that the jams which form annually below Cornwall have their origin in the shoal water extending across the North Channel from Hog Island to the foot of Cornwall Island. These shoals are locally known as 'The Crabs.'

"While there is some diversity of opinion on this point, the writer believes that jams do not originate upon the Crabs but start at the foot of St. Regis Island, as shown by L. J. Salmon, superintendent of dredging for the power company, after a careful investigation of the actual ice conditions in the winter of 1918-9, supplemented by an extended inquiry among the natives living in the vicinity. Mr. Salmon writes:

'February 1, 1919.

'Regarding the ice jam below Cornwall, an investigation of the conditions was made last Tuesday, and it was quite evident that the ice jam formed at the foot of St. Regis Island. The cap at that point was made by the jamming of the floating ice which had come down the river, and from this point back upstream, except, of course, in the bays, the ice cap shows that it has been formed by floating ice cakes having collected and frozen together. This is true of both channels. In the North Channel, after the jam formed about the foot of St. Regis Island, and after the river had frozen over above the Crabs and further upstream tôwards Cornwall, the swifter current below the Crabs wore the ice away until a channel is open from the Crabs almost to the foot of St. Regis Island. The impression one might have is that the jam formed independently at the Crabs, but I think the ice jam really began at the foot of St. Regis Island.

'April 10, 1919.

'Last winter was an open and comparatively mild season and the ice conditions below Cornwall were much different than the normal winter conditions. The head of the ice jam in the North Channel got no further upstream than opposite St. Lawrence Park, about one mile below Cornwall, and in the South Channel only to a point about 3,500 ft. below the New York & Ottawa Railroad bridge. The ice jam was never very heavy during the winter, and the backwater was negligible.

'From inspection of the ice conditions during February and from information obtained from the Indians on St. Regis and Cornwall Island, I believe that at the beginning of the ice season Lake St. Francis froze over up to the foot of St. Regis Island, and at the same time the bays along the shores of Cornwall and St. Regis and other islands, and along the shore of the mainland, froze over and out to the edges of the main current. These open channels then filled up with floating ice and frazil and by alternately filling and shoving down a jam was formed at the foot of St. Regis Island in both channels of the river and the ice cap was built back as far as Cornwall Island.

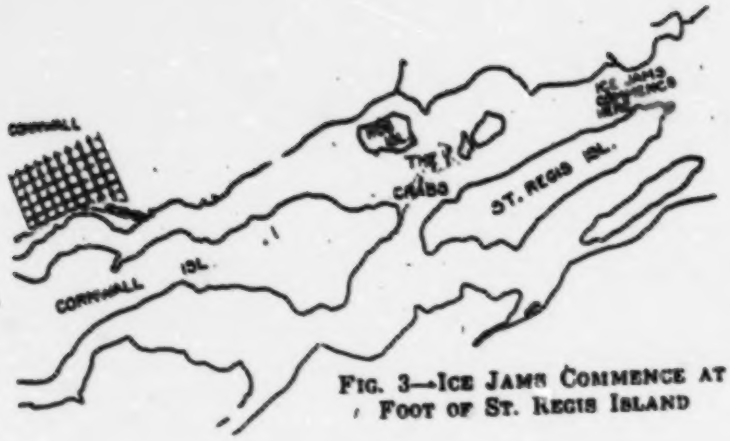

CORNWALL
THE
CRIBS
ST. REGIS ISL.
ICE JAMS COMMENCE HERE
CORNWALL ISL.

FIG. 3—ICE JAMS COMMENCE AT FOOT OF ST. REGIS ISLAND

(Groat, 1920)

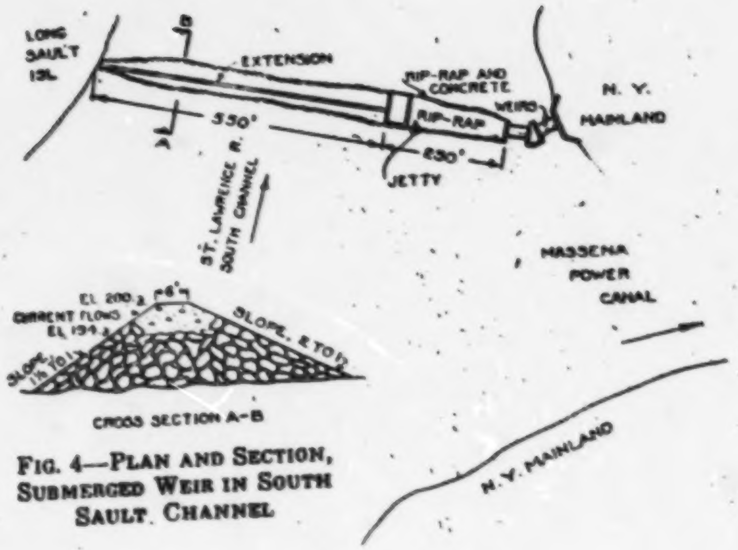

LONG SAULT ISL.
B
EXTENSION
RIP-RAP AND CONCRETE
WEIRS
N. Y. MAINLAND
RIP-RAP
550'
A
230'
JETTY
ST. LAWRENCE R. SOUTH CHANNEL
MASSENA POWER CANAL
EL 200.2
6'
CURRENT FLOWS
EL 194.2
SLOPE, 2 TO 1
SLOPE 1½ TO 1
CROSS SECTION A-B
N. Y. MAINLAND

FIG. 4—PLAN AND SECTION, SUBMERGED WEIR IN SOUTH SAULT. CHANNEL

(Groat, 1920)

'After the river was frozen over up to the foot of Cornwall Island, another jam was formed in each channel of the river-the one in the North Channel between the Hog Island and Cornwall Island, and that in the South Channel between Cornwall Island, Hen Island and the main shore. The jams here became heavier than the jams at the foot of St. Regis Island in the North Channel.

'After January 20th the winter was comparatively mild, with occasional cold periods. The ice jam between Cornwall Island and Hog Island increased gradually, yet during most of the remainder of the winter there was an open channel along the north side of St. Regis Island from the jam at the foot of Cornwall Island to the jam at the foot of St. Regis Island. The jam in the south channel between Hen Island and the mainland, remained and apparently increased, although at times there was open water practically the full length of St. Regis Island, extending from this jam at Hen Island to the jam at the foot of St. Regis Island and Yellow Island, and at the same time there was open water between Hen Island and Cornwall Island.

'The past winter, although late in starting, was about normal during the first fifteen or twenty days as regards temperature, storms and ice-making conditions and, I believe, the above description of the formation of the ice jam at the foot of Cornwall Island, in the North Channel, will, in general, be true for any normal year.'

'August 16th, 1919.

'From my observations of the ice jam below Cornwall last season I believe that the ice cap which formed on Lake St, Francis was the prime cause for stopping the ice which came down the river and collecting it into a ice jam....

"The cause of the jam is certainly not shoal water, for the channels are 50 or 60 ft. deep at the foot of St. Regis Island. The extreme depth at this point may be due to erosion of the river bed, caused by hanging dams which form beneath the ice cap, thus creating high velocities upon the bottom.

"A most careful study of the history of ice conditions at Dodge's Shoal proved that ice seldom or never lodged there or jammed in the shoal water, owing to the high velocity over the shoal. The hydrography of the channels at Richard Bay, in the Big Sny and in the South Sault showed that the water was generally 30 to 55 ft. deep except over the shoals, where it was only 4 to 10 ft. deep with a width fully equal to that of the other channels.

"Hence, the capacity of the water flowing over the shoals to discharge floating ice is much greater than that of the main channel to deliver ice laterally to the South Sault, so there can be no jam on the shoal as a result of shoal water. The only time that jams rest upon Dodge's Shoal is when they have formed down river and have built back upstream. When they do so the ice jam becomes a veritable ice dam on the shoal, turning practically the entire flow of water with its ice load down the Big Sny.

"Safeguard for Cornwall Canal

"This condition has occurred several time in the past, with consequential high water at Lock 21 and in the Long Sault Rapids.... It is, therefore, perfectly clear that prevention of ice jams in the South Sault, which produce ice dams on Dodge's Shoal, will be a safeguard for the Cornwall Canal. If the Massena power plant could have drawn its usual quota of water during the winter of 1919-8, there could have been no such danger of a flood of water and ice in the Cornwall Canal, even though all the remainder of the water for the South Sault had been cut off by an ice jam or a dam of any kind in the South Sault below the canal intake.

"Surface transportivity

"These facts lead immediately to the idea of surface transportivity as the principal natural element governing the capacity of a large river to discharge ice at any cross-section. It is measured approximately by the product of the mean surface velocity of the water and width of the channel at the cross-section in question. This gives a measure of the capacity in square feet of ice per second. If we are not too particular the transportivity may be measured relatively by the product of mean velocity in the cross-section and effective width. Thus the capacity to discharge ice of approximately uniform thickness is sufficiently well expressed by:

"Surface transportivity = $q \div d$ (Equ. 1) wherein q is the rate of discharge of the river and d the mean depth of the cross-section perpendicular to the direction of flow.

"Since q is substantially constant for long reaches or rivers in general, it follows that a relative measure of the transportivity may be indicated by:

"Surface transportivity = $1 \div d$ (Equ. 2) when q is considered constant.

"Referring again to Fig. 2, it will be of interest to examine the cause of jams which form at or near the narrow, deep outlet of Hopson's Bay in the South Sault, indicated by the arrow at the point 'A.' This is an ideal condition for the formation of an ice jam.

"If the stage of the South Sault be assumed at 35,000 c.f.s., the width and mean depth of the outlet are respectively 500 and 30 ft., while the rapids above are much shallower, there being at many sections no more than 4 or 5 ft., with an approximate average at the head of the rapids of, say, 10 ft. Thus the relative transportivities, inlet to outlet, are as 30 to 10, or 3 to 1. More correctly they are:

Transportivity, inlet = 35,000 ÷ 10 = 3,500 sq. ft. per sec.
Transportivity, outlet = 35,000 ÷ 30 = 1,170 sq. ft. per sec.

"This comparison points clearly to the methods to be pursued when it is desired to prevent the formation of ice jams at Hopson's Bay; namely, either to divert the ice from the South Sault so as to keep the the rate of flow of ice below 1,170 sq. ft. per sec., or to raise the elevation of the bed of the stream at the deep section sufficiently to increase the transportivity to the maximum ice flow that can be expected, this maximum being limited by 3,500 sq. ft. per sec.

"Reverse of previous recommendations

"This method of relief from jams by a fill, or transverse ridges, near the outlet of Hopson's Bay is the exact reverse of all previous recommendations that have been made for this case, it being invariably suggested that relief was to be had by dredging.

"If the surface transportivity of a river be made sufficiently high and sufficiently uniform, the river cannot close either by freezing or by jamming. Hence, if the expense were warranted, the jams which originate at the head of Lake St. Francis could be suppressed by means of a properly designed series of dykes and subsurface ridges. This may prove too costly for Lake St. Francis, but the possibility is beyond dispute.

"It is clear from what precedes that the formation of ice jams in the South Sault channel can be prevented by a proper fill, or by transverse subsurface ridges, upon the bed of the outlet at Hopson's Bay, possibly supplementing this by similar protection at other places in the South Channel where the transportivity is dangerously low. But there would be no protection against jams which build back into the channel from down river. Hence it was decided to employ ice diversion at the head of the South Sault, throwing the ice into the Big Sny. This is just what happens every time a jam builds up the South Sault to Dodge's Shoal, a common occurrence in average winter weather. It should be observed in this connection that jams seldom or never build back upstream over the North Sault Rapids (Long Sault proper).

"Figs. 4 and 5 are maps showing the ice-diversion works approved by the International Joint Commission. Fig. 5 shows the wing dam, patented diversion channels and boom extending from the crib at the downstream ice diversion channel across Dodge's Shoal to the head of Delaney Island. Fig. 4 shows a plan and cross-sectional elevation of the submerged weir just below the canal intake, as indicated in Fig. 2. All these structures were operated in a more or less incomplete condition during the winter of 1918-9 and 1919-20.

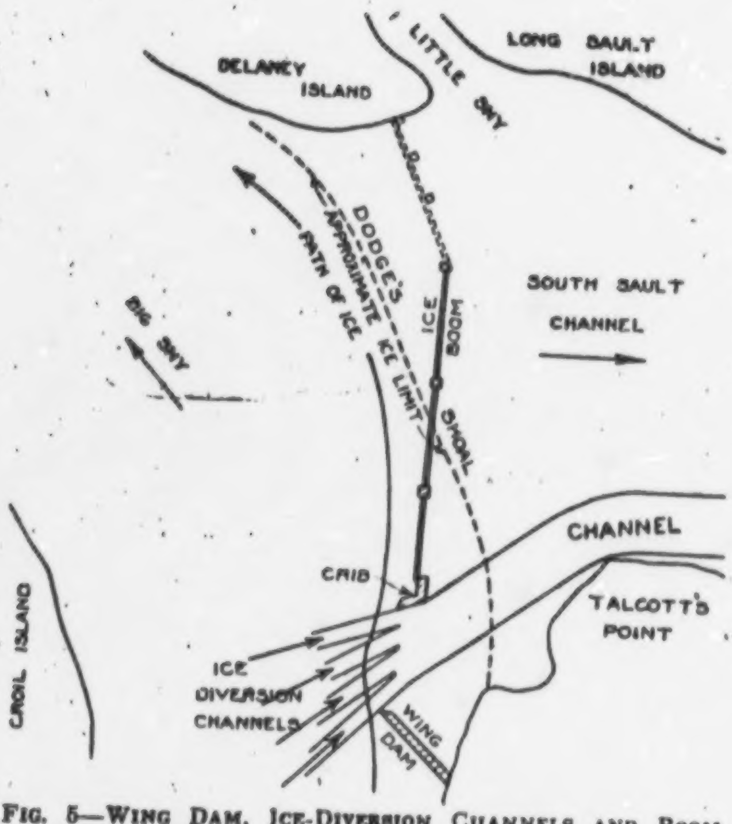

DELANEY ISLAND
LITTLE SNY
LONG SAULT ISLAND
DODGE'S
APPROXIMATE ICE LIMIT
PATH OF ICE
BIG SNY
ICE BOOM
SHOAL
SOUTH SAULT CHANNEL
CHANNEL
CRIB
TALCOTT'S POINT
CROIL ISLAND
ICE DIVERSION CHANNELS
WING DAM

Fig. 5—Wing Dam, Ice-Diversion Channels and Boom Across Dodge's Shoal—Ice Diverted to Big Sny—Water Enters South Sault Free from Ice

(Groat, 1920)

"Ice-diversion channels

"The four ice-diversion channels shown in Fig. 5 are about 40 ft. deep in hardpan sufficiently strong to stand on a very steep slope. The ridges between contiguous channels rise from a submergence of 15 ft. at the upstream side of the upstream channel to about 8 or 10 ft. at the downstream side of the downstream channel, the cross-velocity varying from 1 to 2 ft. per sec. at the inner ends to 7 or 8 ft. per sec. at the outer, or river ends. The main channel toward Croil Island is 40 to 50 ft. deep, and the ice-diversion channels run out into it until the bed of the main channel falls below the grade of the bottoms of the ice-diversion channels.

"The function of the ice-diversion channels and ridges is to throw the surface water with its load of floatage, whether it be ice, weeds or timber, across the channels clear of the boom, while water free from floatage is drawn from the bottom of the river along the bottoms of the channels to the South Sault.

"The hydrodynamic action of the channels establishes itself by causing the layer of water over the channels and ridges to move in a curved path concave in a horizontal direction toward the South Sault, which is really a divergent intake for the power canal below. This produces a potential on the bottoms of the channels directed toward the centre of curvature, that is, inward, or toward the intake. Therefore there is a strong flow to the South Sault along the lower parts of the channels, and this reacts to throw the surface water, between the outer end of the wing dam and crib, toward Croil Island. The result is that little or no ice can get into the South Sault over the ice-diversion channels.

"This theory shows that the ice diversion on Dodge's Shoal takes place under great disadvantage, since the river should curve in the opposite sense, instead of around the end of Croil Island as it does. However, the wing dam assists the diversion, and the channels operate very successfully as they are. Their capacity can be increased by more dredging. In all probability the water near shore upstream from the wing dam is too shallow for the best results. It was intended to deepen here by considerable dredging, but this has not yet been done.

"The boom

"The object of the boom is to create a jam, or ice dam, upon the shoals so as to prevent ice from float-into the South Sault after having been diverted across the ice-diversion channels. The water under the boom varies from 6 to 10 ft. deep, but it is expected that the boom will offer sufficient obstruction to cause the ice to jam ahead of it and build out to the limit line taken by former ice jams as shown in Fig. 5. This is just what occurred during the winter of 1918-9 except that the boom had not been extended completely to Delaney Island, there being a gap of something like 100 ft. left open next the shore.

> "There were several places where ice was drawn under the boom. The result was that considerable quantities of ice passed into the South Sault channel, but sufficiently far from the south shore to escape being drawn into the power canal. The boom is composed of a line of heavy scows drawing 4 or 5 ft. of water, and is held in place by means of cribs, as shown in Fig. 5.
>
> "Submerged weir
>
> "The submerged weir is intended to reduce the slope over Dodge's Shoal, for the safety of the boom. This is accomplished by raising the level of the water at the canal intake to reduce the draft under the boom, otherwise the draft would be so strong that ice would be drawn under in large quantities even though the boom could withstand the punishment. The four elements, wing dam, ice-diversion channels, boom and sumerged weir form a unit which would not work well in the present situation if any one were deleted."

Groat continues to describe model studies proving the effectiveness of the structures. Field testing of the system was inconclusive due to a short period of observation.

In a later paper, Lea (1924) discussed the need for improvement of river ice conditions at Massena.

Bezuglov (1959) feels that a river regulation system would provide one of the best ice jam prevention systems for the Neman River.

> "From the mechanism of jam formation on the Neman River, it follows that the principal cause of jam formation is the time-variation of breakup of the middle Neman and lower Neris expressed in the significant differences of slope and current velocity on those stretches of the river. In such conditions, for prevention of ice jams, it is essential to consider measures that would decrease the slopes of the middle Neman and lower Neris. Thus it is essential to regulate those stretches by dams of a Hydroelectric Station.
>
> "Besides bringing positive solutions to a whole series of state-economic problems (energy, river transport, etc.), the construction of the Hydroelectric Station would bring about the late break-up of head waters and the arrest of the essential ice masses in the reservoirs, which would, in essence, decrease jam formation, and would be a radical way of preventing ice jams."

Morton (1963) discusses some aspects of longitudinal dykes to increase discharge capacity, ice booms, and ice storage diversions. The paper is summarized in the General Ice Jam Characteristics section. Pariset, Hausser and Gagnon (1966) also describe applications of a theory on ice jam mechanism to ice booms, in that section.

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Surging

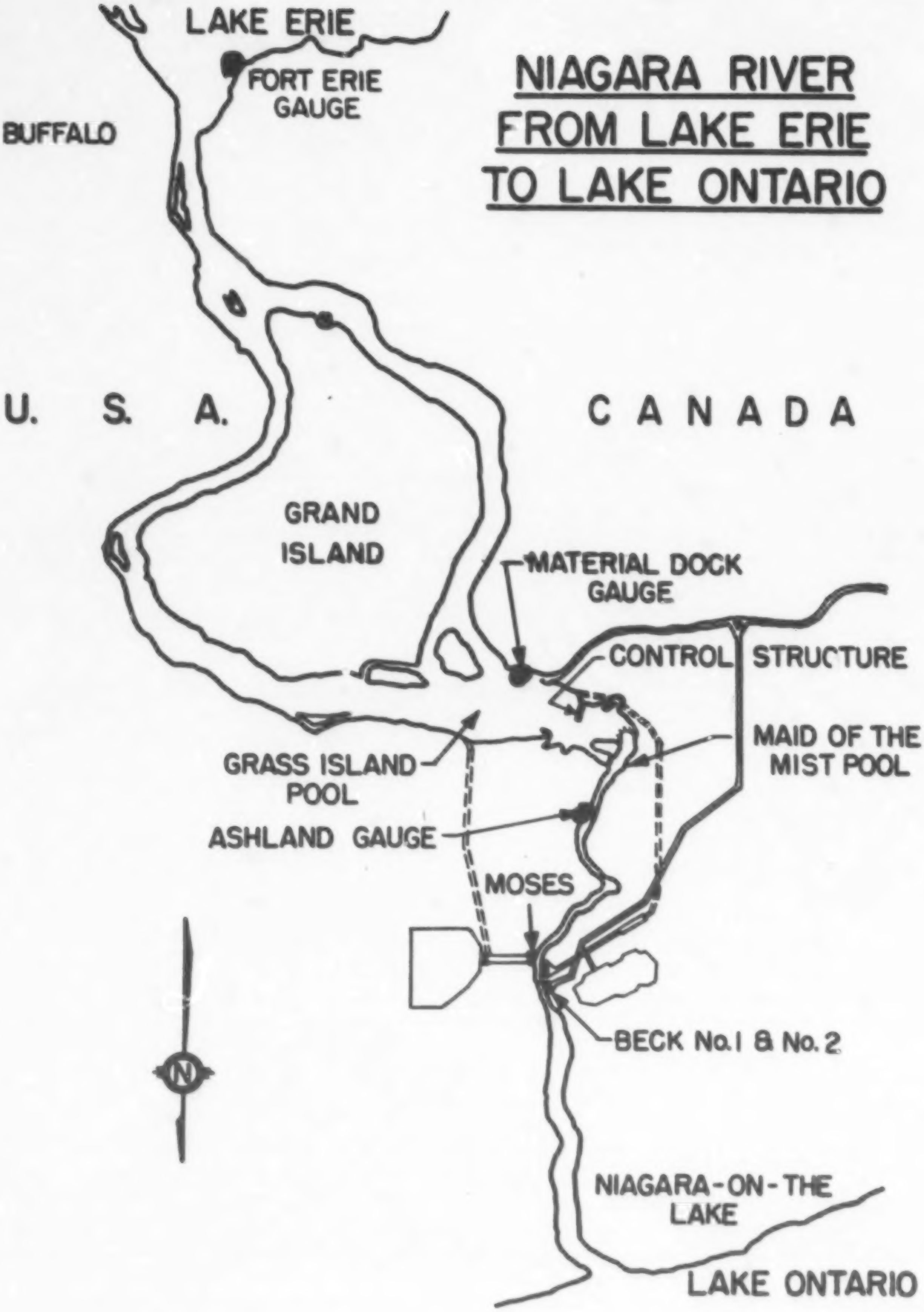
Surging is defined as a sudden change in discharge resulting from the opening or closing of a gate that controls the flow in a channel, or by a sudden introduction of additional water into the channel.

Foulds (1967) describes a control structure on the Niagara River. The primary function of the structure is to regulate flow over the falls. However, it is also used in winter to control river ice by surging.

> "The locations of the intakes to the Power Tunnels on both sides of the river are shown together with the Control Structure and the two falls (Plate IV). The area between the Control Structure and the Power Authority of the State of New York intakes is referred to as the Grass Island Pool. The Control Structure has 18 sluices with gates 100 feet wide which open downward to allow the ice to pass over the top. The maximum depth over the sills is about 10 feet, and over the bottom beyond the end of the Control Structure the maximum depth is about 8 feet. All of the ice leaving Lake Erie, or created by the river, must pass over these outlets."
>
> "If it becomes necessary to remove an ice jam in the upper river, the Control Structure can be most useful. Water levels may be raised several feet to float some of the ice which has become grounded, and then by opening gates, sufficient force may be created to start most of the mass moving towards the dam where it becomes broken by the piers and the hydraulic action combined. The remaining grounded pieces may be split by the boats until they float away by themselves. The water level raising procedure is rather lengthy as it requires a large quantity of water and about one day to arrange and complete."

Foulds (1964) also describes the structure in an earlier paper:

> "...The Control Structure is used to adjust depths and currents and thus to direct water and ice movements. It may be operated also in a rather limited way to float ice which has become grounded. It was designed to withstand the impact of large masses of ice and to break them into such smaller pieces through hydraulic action.
>
> "Because the (power) intakes tend to draw ice towards them it was obvious that channels to carry ice away were essential. Unfortunately, along the American shore, the river was very shallow over a huge area, and it was necessary to excavate a channel 1000 feet wide with a minimum depth of ten feet in the 500 feet adjacent to the shore. This excavation was initially almost two miles in length but a further extension of three quarters of a mile was found to be necessary and it now ends approximately 1000 feet downstream of the Control Structure.


LAKE ERIE
FORT ERIE GAUGE
BUFFALO
NIAGARA RIVER FROM LAKE ERIE TO LAKE ONTARIO
U. S. A.
CANADA
GRAND ISLAND
MATERIAL DOCK GAUGE
CONTROL STRUCTURE
MAID OF THE MIST POOL
GRASS ISLAND POOL
ASHLAND GAUGE
MOSES
BECK No.1 & No.2
N
NIAGARA-ON-THE LAKE
LAKE ONTARIO

(Foulds, 1967)

PLATE IV

"On the Canadian side similar excavations were undertaken to produce a minimum depth of eight feet. In addition, walls were constructed for ice control purposes. The upstream wall is one-third of a mile in length and creates an acceleration channel. By manipulating the three inshore gates in the Control Structure, the rate at which ice may be drawn away from the Beck Intakes may be controlled. The downstream wall is 2000 feet in length and was required to maintain adequate depths for transporting ice to the cascades and to maintain headwater levels at the Ontario Power intake."

Ice evacuation problems at dams are discussed by Chugaev (1967).

"1. The capacity of evacuation of ice in a wetted section can be given by the value

$$\Lambda = B\,\delta \cdot v_s\,, \tag{1}$$

where B is the width of the flowing surface, δ the thickness of the passing ice in one, two or several beds, v_s the average superficial velocity. For a rectangular bed, Λ can be as expression (1) under the form:

$$\Lambda = \beta \cdot \delta \left[Q : (h - 0{,}9 \cdot \delta) \right] \approx \beta \cdot \delta \, (Q : h)\,, \tag{2}$$

Q is the discharge of water, h - depth of the channel, 0.9 δ the string or pull of the ice, β - the coefficient of passage of the average velocity at the velocity v_s, (equal to 1.2 - 1.3). For the parabolic bed one obtains a similar relation.

"2. The volume of ice Λ passing in unit time through the wetted section does not depend on B; it is inversely proportional to h (see eq. 2). This is why in proportion as it approaches the dam, the value of Λ, at δ = a constant, can be diminished.

"3. The ice can always accumulate in the upstream pool; it there produces an accumulation and the value δ is augmented with time in proportion as it approaches the dam. The chosen section immediately upstream from the dam can be characterized at the beginning of the ice drift by Λ_{min} when $h = h_{max}$. In using equation (2) one can analyze the variation of Λ through time for the given section (in relation to variation of δ)....

"4. One knows the dangers which occur near the ice breakup:

a) with an incomplete opening of the vein, the ice blocks can plunge under it causing damage,

b) falling into the downstream pool the ice blocks are likely to cause grave damage to the revetments, at the time of impact on the dam they can damage the piles and the footings;

c) the damages to the dam can take place after the impact of the ice blocks pass below the crown;

d) in the sluices of the dam a 'forced' ice jam can be produced (causing the formation of a 'cupola' of ice); there, the section of flow will be reduced, one can get the inadmissible raising of the water level upstream from the dam. It is also necessary to take to account that the depth of the water on the crown of the dam is always lower than the depth h in the upstream pool; this is why one must allow that for Q = constant (the long outline of the breakup) the capacity of evacuation of ice λ' of the sluices of the dam is always greater than λ'', in the section upstream from the dam. Thus, for Q = constant there is not the danger of accumulation of the ice immediately upstream from the dam. Therefore, in the case of partial evacuation of discharge (one part being used), one can obtain $\lambda' < \lambda''$. An ice jam 'of accumulation', taking place after the amassing of the ice upstream of the dam, can cause undesirable flooding of the banks. For the purpose of avoiding the formation of similar ice jams which one must choose the discharge H, on the sill the sluices for the evacuation of ice, in respect to the following conditions:

$$H \leq H'_{max} \quad \text{where} \quad H_{max} = \frac{Q_e}{Q} \kappa \cdot h , \qquad (3)$$

here: Q_e -discharge of water evacuated through the ice evacuation sluices K - coefficient of reduction of motion of the ice in the sluices (in first approximation it is or it appears to be equal to 0.75).

"5. It is to distinguish two different types of ice jams by their physical nature; a 'forced' ice jam and that 'of accumulation' which are formed, by example, at the extremity of the curve of the backwater where the value λ begins to quickly decrease along the stream. It is useless to struggle against the latter ice jam by any mechanical means (explosions, etc.).

"6. In elaborating the projects of the works of evacuation of the ice it is necessary to consider the following:

a. One must always hold $H > H_{min}$ with $H_{min} = 1,3\delta$. Otherwise the isolated ice blocks moving with the current or pushed by the wind entering into the sluices will become susceptible to impacting upon the crown of the dam.

b. The special works for the evacuation of ice can only be seen in the case of the danger of formation of an ice jam producing an inadmissible rise in water level. A similar ice jam occuring in the presence of a dam of moderate height, where the relation between the depth of the pool and that of the river into which it flows is small, the length of the pool is insignificant and the important part of the discharge of the river is evacuated through underwater openings (which are not designed for evacuation of ice).

c. In the project of the special works for the evacuation of ice, the width b of the mouths must be chosen conformable to the well-known condition $b > 15\text{-}25$ m. (to avoid a 'forced' ice jam).

d. The total width B_λ of these works must be chosen such that the load or weight H is equal to:

$$H = \nabla R.N. - \nabla \qquad \text{(crown of bridge)} \tag{4}$$

and that the discharge is equal to

$$Q_0 = Q_\lambda - Q' \tag{5}$$

Q' being the discharge of the submerged mouths, Q_λ the discharge of the ice jam.

"H and Q_0 being known, one can easily obtain, with the aid of a well-known equation of overflow, the unknown value of B_λ . In effecting such a calculation it is necessary to respect the condition below:

$$H_{min} \leq H < H_{max} \tag{6}$$

where H_{max} is determined by the expression (3) supposing $Q = Q_\lambda$. If $H_{max} < H_{min}$, one must increase Q_0 by diminishing Q' for which the condition is given by $H_{max} > H_{min}$; it is desirable that $H = H_{min}$.

"We have given a position of the problem relative to the calculations of ice evacuation works (based on the idea of the capacity of ice evacuation) which can have a practical application."

Brachtl and Komora (1967) describe some model tests to develop on ice control structure system for ice jam prevention at a reservoir proposed for the Danube River.

"Design studies for several alternative solutions of water schemes has been developed in recent years on the Czechoslovak - Hungarian stretch of the Danube River....

"At present state during heavy frosts there is an intensive frazil ice motion on the Danube. In some years a continuous ice cover is formed of frazil ice floes. As a result of streaming velocity, water depth and dimensions of floating ice-slush floes jamming of floes occurs, thus reducing the discharge cross-section and creating danger of ice flood. After completion of the water scheme ice cover is going to be formed in the reservoir and at the end of the backwater in the region of Bratislava ice floes floating down from the upper track will cause jamming. Analyzing this problem it can be seen that safety of the town can be increased especially by providing the possibility of skimming the accumulated ice through the reservoir. This manipulation necessitates establishing of at least minimum surface velocities in the reservoir in this way, as to prevent the repeated filling and freezing of the way, loosened by means of the ice-breaker.

"The study on aerodynamic model in the scale 1: 3000/1000 enabled us to measure and evaluate the velocity conditions in the reservoir, maintaining the backwater. In the upper part of the reservoir, where only shallow water exists in the innundation, the water stream will be concentrated in the river channel. In the lower part streaming will be uniformly distributed within the reservoir width, the streamlines being not in the direction of the original river channel. As a result only a small percentage of the discharge is flowing through the channel.

"In Fig. 1 water surface elevations are presented in the longitudinal cross-section of the reservoir for attaining mean cross-sectional velocities in the river bed of 0,2 - 1,6 m/s at average discharge of the Danube of 2000 cub. m/s, for two extreme cases: for the case of the whole discharge concentration into the river channel/ broken line/ and for the case without the discharge concentration / full line/. Without the discharge concentration into the river channel the velocities are only low and therefore it was necessary to test the influence of concentration embankments on the streaming in the reservoir.

"Nine proposals of concentration dams in the reservoir were designed and tested on the aerodynamic model. For two solutions a detailed research was performed on a distorted model, constructed in the scale 1 : 200/75. For modeling of slush ice floes we have used polythene crushed material with a specific weight of 0,92. Water, needed for skimming of 1 m^2 of ice cover was investigated and a rather favourable influence of concentration dams on the water consumption was established.

"In arrangement 1 /Fig. 2/ of the concentration dam water, needed for transportation of 1 m^2 of slush floes is 70 cub. m. Disadvantage of this solution is the circumstance that the big ice floes, which can be loosened in the lower part of the reservoir during the water level decreasing, can close the broken way in the ice cover.

"At arrangement 2 /Fig. 3/ of the concentration dam a continuous forward motion of ice floes to the weir is attained. After decreasing the water level in the reservoir by 2,5 m, 25 cub. m of water is sufficient for skimming 1 m^2 of ice floes. By connecting of the concentration dam with the dam of the reservoir on the left side of the weir the velocities in the lower part of the reservoir are increased, thus influencing favourably the ice skimming. The lateral channel as well as the left side of the reservoir behind the concentration structure is emptied in a smaller extent than at the arrangement 1. Analogous results on water consumption were obtained for the hydroelectric power plant Wolfsthal-Bratislava on the Danube during the investigation on a non-distorted model 1 : 60. Thus the possibility of modeling of ice skimming on distorted models is confirmed.

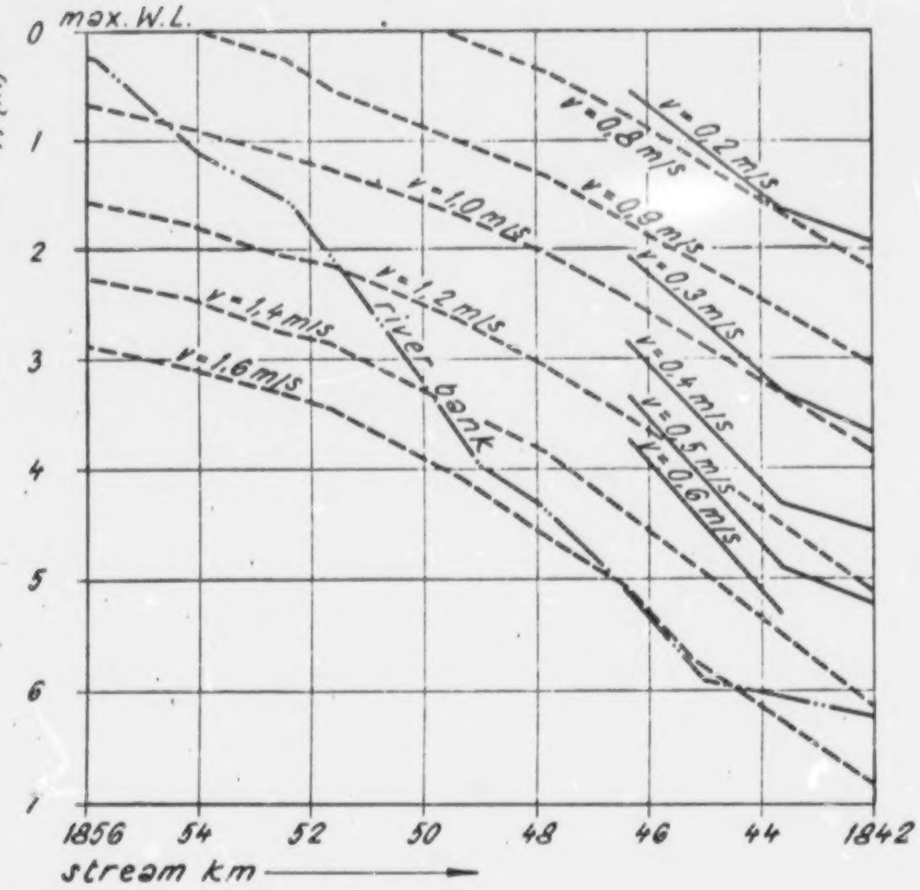
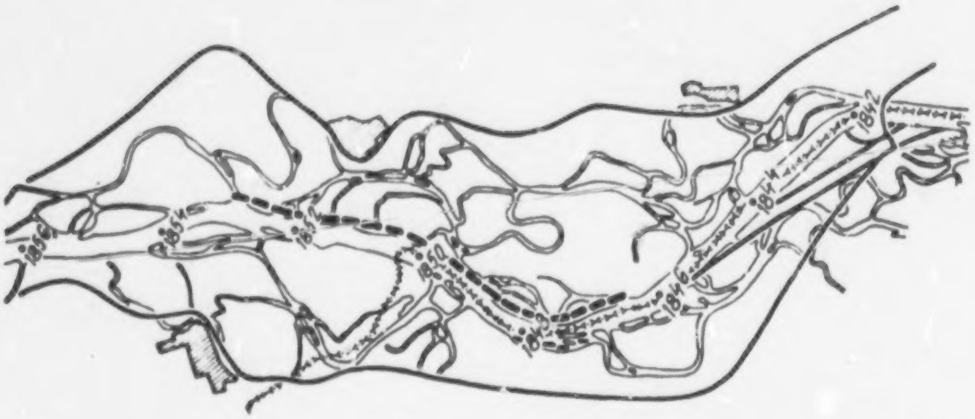


Fig. 1 Water elevations in the longitudinal cross-section of the reservoir for attaining mean cross-sectional velocities in the river channel 0,2 - 1,6 m/s at a discharge 2000 cub.m/s.

(Brachtl and Komora, 1967)


1856
1854
1852
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1848
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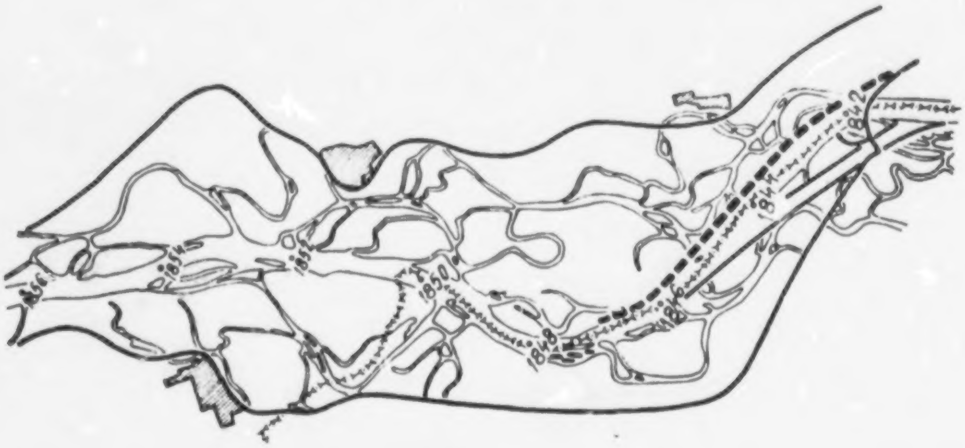
1844
1842

Fig. 2 The first arrangement of the concentration dam in the reservoir.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1842

Fig. 3 The second arrangement of the concentration dam in the reservoir.

(Brachtl and Komora, 1967)

"The result of this study is a design of submerged concentration structure according to the arrangement 2, the crest of which is 2,5 m under the operation level. At maximum flood discharges no critical streaming will occur over the crest of this structure and therefore the flood water levels will not be increased."

Pariset and Michel (1959) describe ice spillways for runoff river hydroelectric stations. According to Gotlib (1961) 12 meter wide ice spillways were effective in preventing ice jams at a hydroelectric plant on the Angara River.

Komarovskii (1933) recommends ice chutes for removing ice near hydroelectric dams.

Hess (1950) describes how power plants can prevent ice jams by raising water levels sufficiently to float the river ice before jams are formed. He warns that once a jam is formed this method is usually ineffective for removal.

Shaitan (1967) discusses some hazards to river structures due to fluctuations in water levels in the presence of an ice cover. The study has applications to surging techniques.

"1. Any, even insignificant, change in the water level of a basin after the formation of a solid ice cover calls forth a corresponding displacement and deformations of the ice near the plane of its freezing to the members of hydraulic engineering structures. In the zone close to the exterior face of the structure, the stresses in the ice grow. The development of the deformations being considered depends in the main on the magnitude and intensity of the water level fluctuations, and also on the physical and mechanical properties and the thickness of the ice. The general nature of the ice deformations in this instance, however, follows the same lines, which makes it possible to adopt a single scheme for investigating them.

"2. With considerable lowering or rising of the water level the stresses in the ice may reach their ultimate values. This will cause a crack to appear in the ice sheet near the structure (Fig. 1), parallel to its face. On the exterior face of the structure there remains a free ice cantilever frozen to it that has broken away from the remaining part of the ice sheet.

"3. Upon a further lowering of the water level and bearing of the ice along the first crack on the underwater part of the structure, other cracks may appear in the ice sheet in its following heaviest stressed sections.

"4. Generally the moment when the first crack appears near the bank is dangerous for the stability and strength of the structure elements resisting the load with such deformations of the ice.

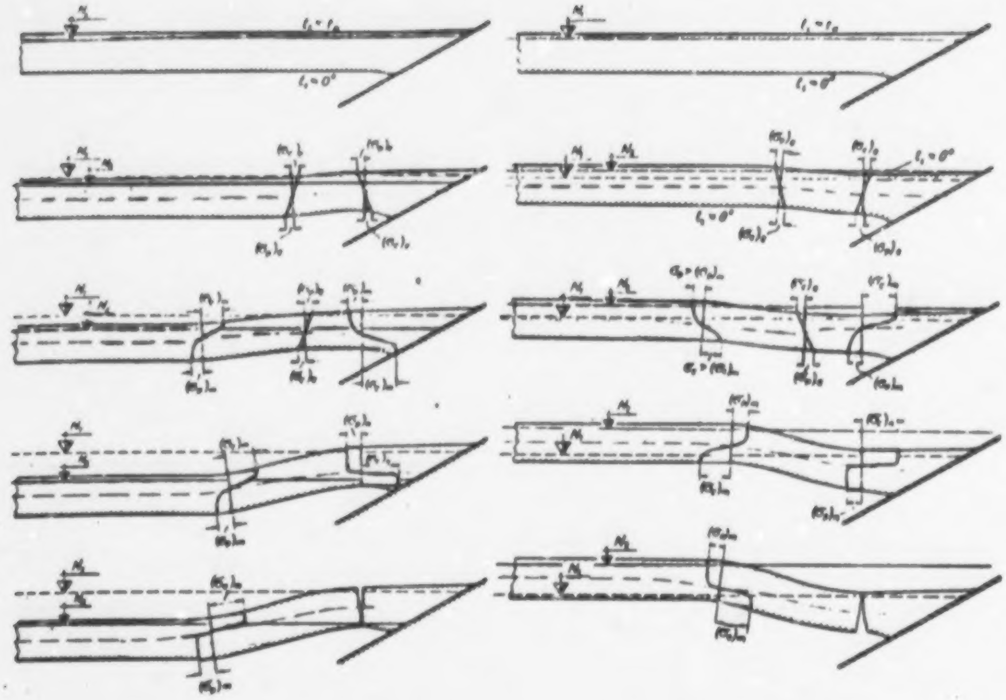

Fig.1. Diagram showing deformations and stress distribution in ice sheet upon changes in water level after the ice has frozen to the structure:
N_1 - water level when surface freezes; N_2 - variable water level; $(\sigma)_e$ - stresses in ice within elastic limits; $(\sigma)_m$ - stresses in ice beyond elastic limits; $(\sigma)_n$ - stresses in ice at yield point; σ_n - tensile stresses; σ_c - compressive stresses; t_1 - temperature of ice sheet surface layer; t_a - air temperature.

(Shaitan, 1967)

"5. The load which is transmitted from the deformed ice to the structure or a separate element thereof has the form of a moment, a longitudinal and a lateral forces acting in the end section of the ice cantilever frozen to the structure. The design scheme of application of the equivalent forces, taking into account the influence of the ice sheet part separating from the bank cantilever, can be represented only by a moment load, seeing that the longitudinal and lateral forces in this case reduce the action of the bending moment. Bearing in mind the approximate nature of the initial parameters used for analysis, such an exclusion of these forces, amounting to from 5 to 15 per cent of the total load, increases the reliability of the calculations.

"6. The magnitude of the maximum moment load, transmitted by the ice cantilever to the structure and taken as the design load when determining the stability and strength of the members, is determined by the sum of the internal ultimate stresses in the section coinciding with the plane of the crack nearest to the structure. A crack appears in the ice sheet when the stresses in the ice reach the stage of plastic strains, i. e., when the stresses in the section are distributed in accordance with a plastic hinge and reach the yield point.

"7. Ice is an anisotropic elastoplastic or elastoviscous, depending on the temperature, physical body. Its yield points exceed the elastic limits 30 to 50 times, on the average. Upon a slow growth of the deformations, stress relaxation takes place, which must be taken into account for properly determining the design loads on the structure depending on the intensity of the water level fluctuations.

"8. The design moment load transmitted to a structure or its separate members from a frozen on and deformed ice sheet upon a reduction or increase in the water level is determined, with a view to the initial conditions for analysis, by the formula,

$$\Sigma M_x = \frac{b\delta_x^2}{6} \frac{(\sigma_p)_p (\sigma_c)_p}{(\sigma_p)_p + (\sigma_c)_p} (1 + 2K_B) \qquad (1)$$

where b = effective length of face of structure or separate element thereof along the water level line, m

δ_x = effective thickness of ice cover in metres, taken equal to the thickness of its crystallic layer; for preliminary calculations the thickness of the crystallic layer can be taken, depending on the conditions of ice cover formation, equal to $\delta_x = (0.8\text{-}0.9)\,\delta_i$ in which δ_i is the total thickness of the ice sheet at a reasonable distance from the bank $(\sigma_p)_p$ and $(\sigma_c)_p$ = design values of crystallic ice stresses in tension and compression, respectively; they are determined for values of the factor K (allowing for the reduction of the stresses in the ice with time) less than 0.85 by formula (2) and (3) in t/m^2, while with K > 0.85 they are taken equal to

$$(\sigma_p)_p = (\sigma_p)_n \; ; (\sigma_c)_p = (\sigma_c)_n ; \; K = \frac{(\sigma)_p}{(\sigma)_n} \; ;$$

$(\sigma)_p$ = design values of crystallic ice stresses in tension or compression

$(\sigma)_n$ = yield points of crystallic ice in tension or compression

$$(\sigma_p)_p = (\sigma_p)_n \, e^{-\frac{\Delta}{r}} \tag{2}$$

$$(\sigma_c)_p = (\sigma_c)_n \, e^{-\frac{\Delta}{r}} \tag{3}$$

and $(\sigma_c)_n$ = yield points of crystallic ice in tension and compression, respectively in t/m^2; their values are taken for the upper part of the ice sheet depending on the design temperature of the air, and for the lower part for a temperature of 0 deg C when the water level drops and within 0 to 2 deg C when the level rises.

K_E = coefficient of moduli of elasticity, taken equal to unity when $K < 0.85$ and to two when $K \gg 0.85$

e = base of natural logarithms

Δ = time in hours during which the ice sheet deforms by an amount approximately equal to the thickness of the ice upon lowering or rising of the water level

r= parameter characterizing the intensity of relaxation, $r = \frac{\mu}{E}$

μ = ice viscosity coefficient in t-hr/m^2

E= statical modulus of elasticity of ice, t/m^2."

Yestifeyev (1967 mentions some aspects of surging in hydroelectric reservoirs.

Without amplification of the methods required, Kravchenko (1959) recommends surging as an ice jam prevention measure for the Dniester River.

Bock (1957) examines some ice problems encountered by power plant operators in Europe. Experience with ice of the Jochenstein Dam on the Danube is covered in detail. Some surging techniques are described.

"Removal of ice over weir.

"Removal of ice over the weir is unsatisfactory owing to the low surface current (0.2 to 0.3 m^3/sec). The mere lowering of the upper sluices gates is not sufficient to secure the movement of the ice floes and to remove them continually downstream. The densely drifting ice floes get stuck 20 to 50 m upstream from the weir especially with a wind direction opposed to the current. A somewhat better efficiency can be obtained by repeatedly lowering the sluice gates to an overflow of about 2 m thus increasing the incline, and then by damming up again. This process was carried out experimentally 2, 3 and 4 times within 24 hours, whereby one third of the time was devoted to lowering the water level and two thirds to refilling, according to water passage. As far as the variable influence of the ice mass accumulated in the range of the river, the size of ice blocks, ice accumulations, head wind, etc., allow an estimate, such a procedure of longer duration might result in satisfactory dissolution."

Siegfried (1957) reports in the use of surging in France.

"Raising and lowering of stream levels also will aid in the dispersal of ice drifts. This variation in the water level may be achieved artificially by maneuvering dams, raising and lowering of sluice gates. This is quite useful in disengaging the ice pack at the moment of thaw."

Surging

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Channel modification

Any constriction in a river channel is a potential location for ice jam formation. Streamlining a channel can, thus, promote free ice passage and prevent jam formation.

Laszloffy (1948) feels that "The regulation of the river channel, however burdensome it may be, is undoubtedly the best, since it aids navigation at the same time." He refers to river regulation as change in channel configuration to promote the smooth flow of ice.

In a more recent report, channel modifications are described by Horvath and Laszloffy (1957).

> "The most important means of reducing the duration of the ice period is river regulation; the smoother its path the more difficultly the ice stops, the less solid it becomes, the more easily it passes down. River regulation also greatly reduces the danger of icy floods."
>
> "The favourable effect of channel regulation on the passage of ice is manifest at first sight from Fig. 7 and 8. The elimination of sharp bends and of islets, or the reduction of their number, definitely makes the stoppage of ice more difficult and the passage of broken-up ice smoother.
>
> "The beneficial effect of this is numerically evident from the following data: The regulation of the Budapest section, and of that downstream from Budapest was executed, as aforementioned, between 1871 and 1885. On the period of 1818-1865 ice records of Budapest covering 31 years are complete. In the average of these years in winter the ice on the Danube was stationary for 25.1 days. The average of 70 winters from 1887 to 1956, on the other hand, is only 12.6 days....
>
> "To make the comparison still more illustrative 10 winters each were selected from among the years of average December - February mean temperature identical (-0.22°C) before and after the regulation, and it was found that while in 8 out of the ten years before the regulation, on a total of 200 days the ice was stationary at Budapest, and the maximum was 48 days; out of 10 years after the regulation this occurred only in 6 years and lasted only on 82 days, the maximum being 23 days.
>
> "Still more convincing is the comparison if water stages are considered. Thirty-five years each were chosen from among the years of equal mean winter temperature before and after the regulation, and it was established on which month fell the maximum annual water stage. It

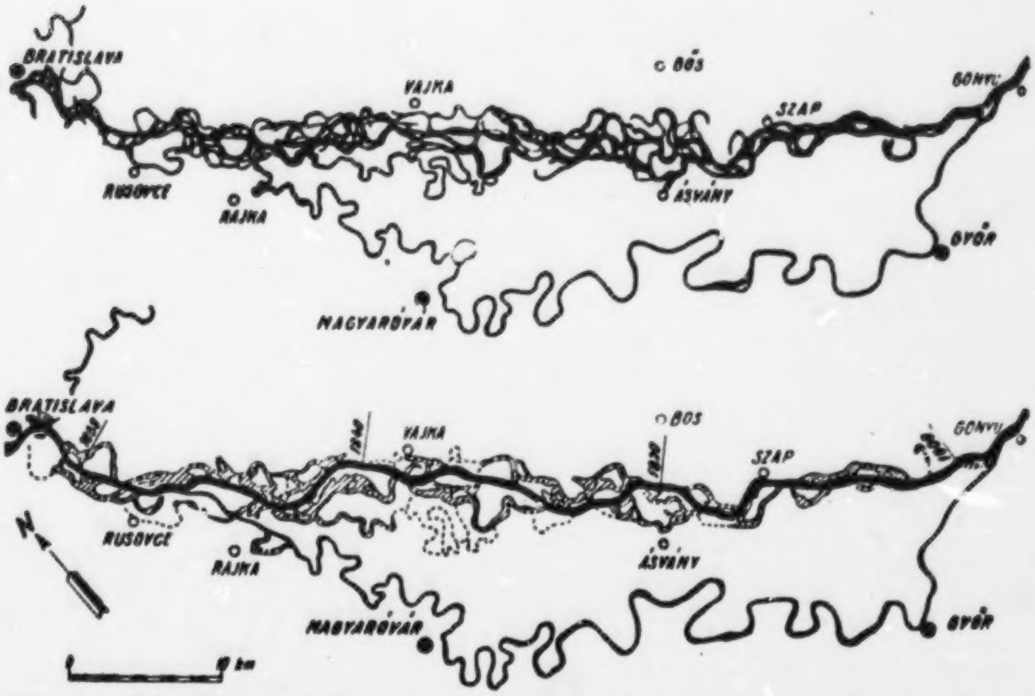

BRATISLAVA
BÖS
VAJKA
GONYU
SZAP
RUSOVCE
RAJKA
ÁSVÁNY
GYŐR
MAGYARÓVÁR
N
0
10 km

Fig. 7. — The Danube section 1.860 - 1.800 km before the regulation (around 1.830) and after.

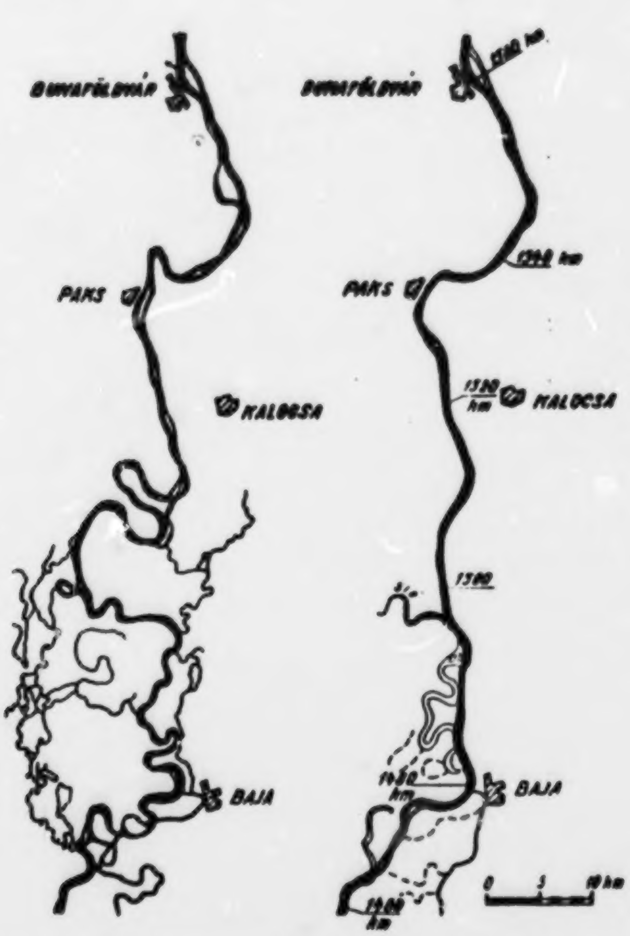

Dunaföldvár
1560 km
PAKS
1540 km
1520 km
KALOCSA
1500
BAJA
1480 km
1460 km
0
5
10 km

Fig. 8. The 1560 - 1460 km Section of the Danube before the regulation (around 1830) and after

(Laszloffy, 1957)

was found that while prior to the regulation the annual maximum fell on February, in 25.8% of the cases, and in 48.7% of the cases it fell on the four winter months, after the regulation the respective % ages fell to 8.6 and 22.9 and most of the maxima shifted to June-July when the river actually discharges the maximum flow....

"The regulation can be successful from the point of view of the regimen of ice only if it extends on the whole of each of the longer reaches of the river, forming natural units."

Llamas (1965) describes channel modifications to promote free ice passage.

"In the region called the 'Dead Waters' a certain number of operations of amelioration or correction of the river bed have been executed or proposed. The principle object of these operations is to eliminate the obstacle to the passage of ice during the breakup and to relieve, as much as possible, the critical points of ice jam formation.

"The studies concerning the movement of ice in a river at the moment of the destruction of the cover have shown that for a rapid and continued flow of ice blocks, it is necessary:

1) that the section of flow be as uniform as possible throughout the river,

2) that the average water depth be at least 3'.

But, in several places these conditions are not met because of the existence of pronounced curves, large boulders, islands, shoals, etc., where the ice becomes arrested during a more or less long period.

"The kind of operation is of a classic type; dredging, adjustment of the bed and the banks, turning the mouths of the tributaries, etc. whatever the case.

"All these operations have been projected with the condition of not modifying in any way the base level of the water, that is to say that if the old section controlled the level upstream at a certain discharge, after the operation, the new section would also control the level upstream for a discharge equal or superior to the low-water discharge (Tison, 1953).

"By way of an example, one includes the process of the following calculations for the operation at the mouths of the Nadeau and Lessard Rivers (Fig. 33).

"First, the upper limit of the discharge for this section of the river in a natural state was calculated, it controlled the upstream level. Figure 34, shows that this discharge was 18,000 cfs. The same calculation was

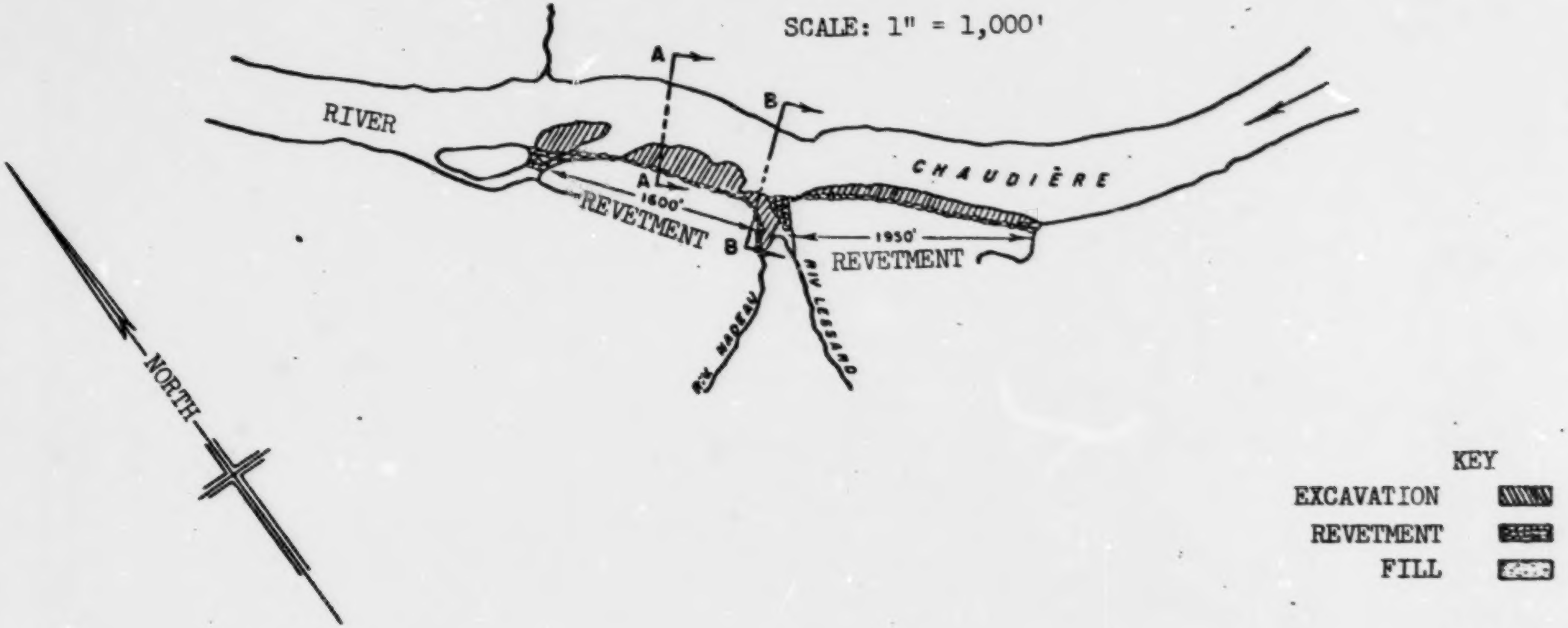
FIGURE **No. 33**

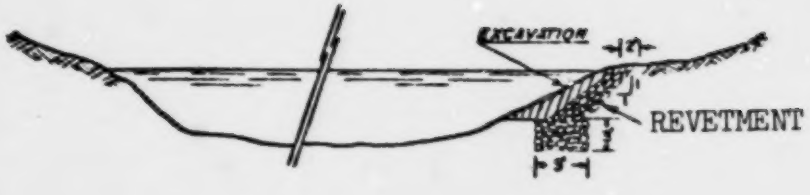
CHAUDIERE RIVER (Llamas, 1965)

REMEDIAL OPERATIONS: REGULARIZATION OF THE BED AT THE MOUTH OF THE NADEAU AND LESSARD RIVERS

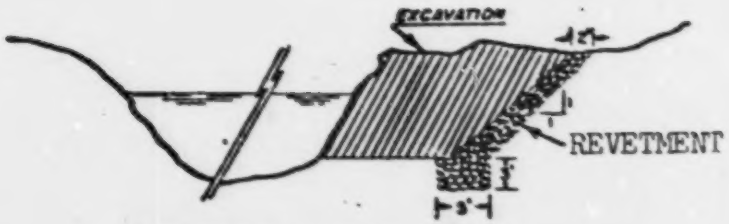
STE-MARIE PARISH COMTE DE BEAUCE

SCALE: 1" = 1,000'


RIVER
CHAUDIÈRE
A
A
B
B
1600'
REVETMENT
1950'
REVETMENT
RIV NADEAU
RIV LESSARD
NORTH
KEY
EXCAVATION ▨
REVETMENT ▩
FILL ▒


EXCAVATION
REVETMENT
5'

SECTION TYPE 'A-A'
SCALE: 1" = 20'


EXCAVATION
REVETMENT
5'

SECTION TYPE 'B-B'
SCALE: 1" = 20 '

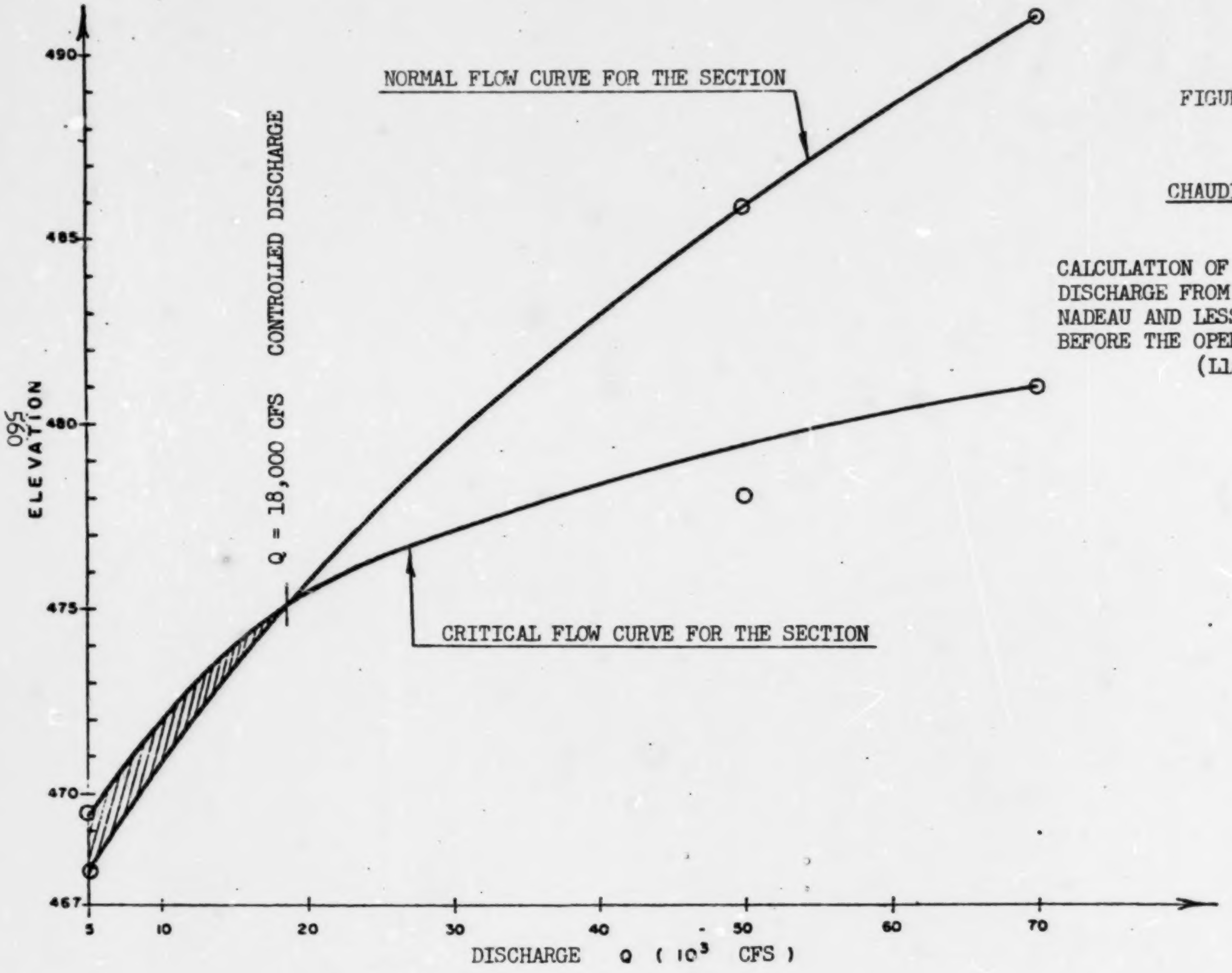


FIGURE No. 34

CHAUDIERE RIVER

CALCULATION OF THE CONTROLLED
DISCHARGE FROM THE MOUTH OF THE
NADEAU AND LESSARD RIVERS
BEFORE THE OPERATION
(Llamas, 1965)

made for the new modified section and a discharge of 5,500 cfs. was obtained, below which the section controlled the upstream level (Fig. 35). Since, the discharge of 5,500 cfs. is sufficiently above the low-water discharge, it can be concluded that the operation has not modified the base level of the water."

Golek (1957) describes the results of channel modifications on another river. "The largest number of ice jams on the Oder River were observed in 1929, that is, above 20, instead of only 12 observed on this river in the postwar period. Before 1929, the abundance of ice jams were on the Oder River in 1907-1909 and 1912, when every year several ice jams were observed. The greatest number of ice jams on the Oder River were noted in the vicinity of Wroclawa and Trestna to 1927, the probable appearance being 40 to 50%. Ice jams in the profiles mentioned were not observed after this period"

Dredging river channels is discussed by Siegfried, (1957).

"After the dredging of the maritime stretch of the Loire, ice jams in the port or downstream of Nates became rare. This is due to the great depth achieved by the dredging. Upstream, in sections of shallow depth, ice jams are still common. However, ice may become grounded upon sand bars in the lower stretches and create problems. Ice in estuaries is brought down by the rivers from upstream and, depending on the severity of the winter, may form ice packs in the marine estuaries. This is rare but in extremely cold winter, this may happen. Dredging of the estuary reduces the chance of ice jams, but during extremely hard winters, pack ice may form."

In a report by the Detroit District, Corps of Engineers (1966), ice jamming conditions in the Kawkawlin River, Michigan are analyzed. A method for prevention of floods caused by ice jams is developed which involves channel enlargement and elimination of bridge constrictions.

Garner and Frankenstein (1966) studied ice conditions on a short reach of the White River from its confluence with the Connecticut to Sharon, Vermont. They recommended removal of large boulders in three segments of the reach and the remains of an old dam in order to prevent ice jamming in the area.

Assur and Frankenstein (1963) conducted a similar study near the confluence of the Mohawk and Connecticut Rivers. Several changes in channel configuration were recommended. However, an ice retention structure was described as the 'most effective solution' for preventing ice jams.

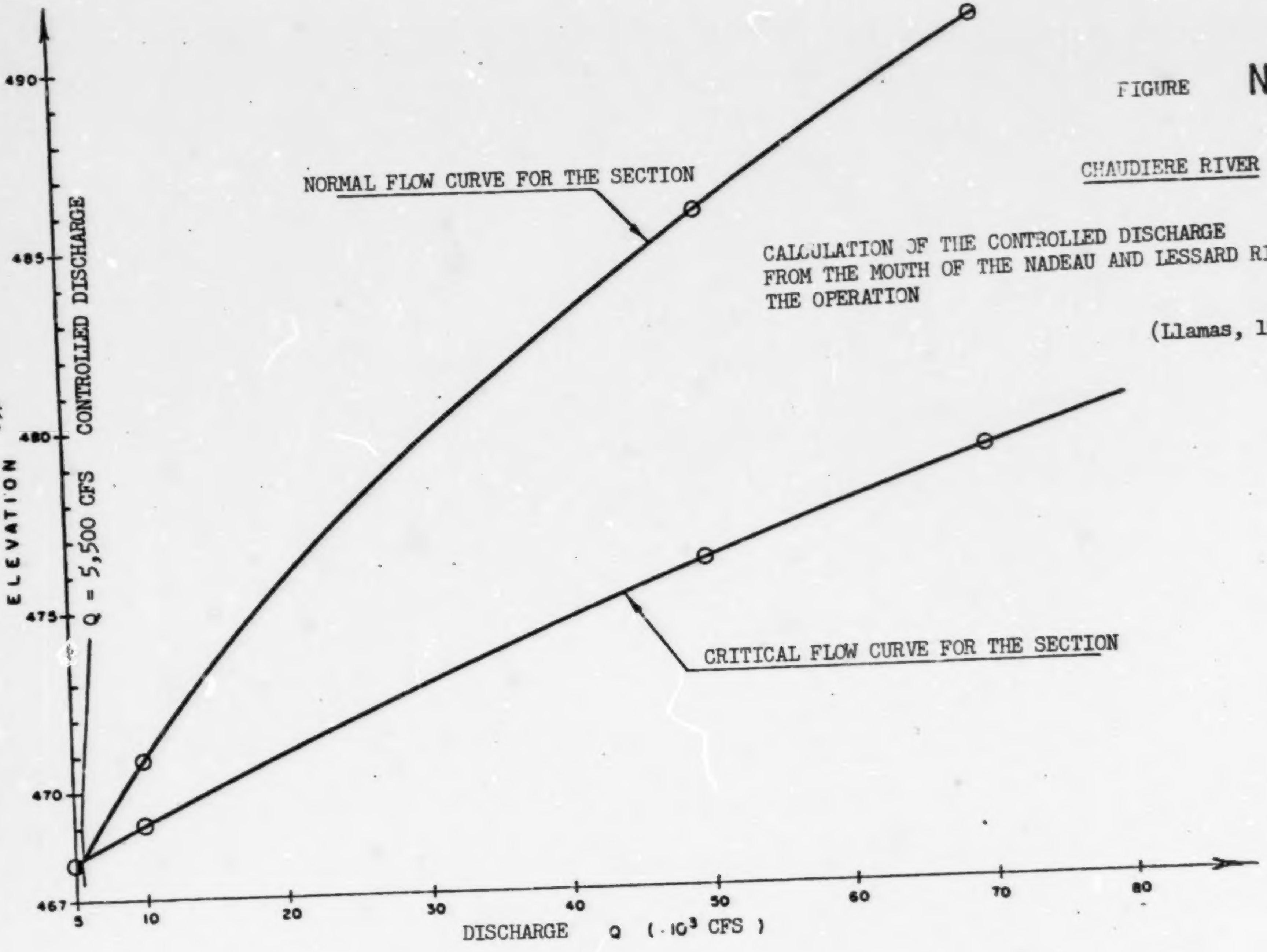
Dintruff (1946), briefly describes some successful changes in channel configuration of the Genesee River near Rochester.

FIGURE No. 35

CHAUDIERE RIVER

CALCULATION OF THE CONTROLLED DISCHARGE
FROM THE MOUTH OF THE NADEAU AND LESSARD RIVERS AFTER
THE OPERATION

(Llamas, 1965)



Groat (1918) describes some early model tests for diverting surface water flow from canals. The method would reduce the surface transportivity of a river in the area of a canal and thereby reduce the probability of ice jams in the canal.

> "... The proper way to divert floating materials is to make the surface currents carry them away, rather than use a boom, which, in reality, opposes, instead of assists, the movement of floatage, and has little or no effect at all on materials suspended below the surface of the water....
>
> "As it is principally the surface currents which carry floating materials, it will be possible to measure, more or less exactly, the transporting capacity of a river at a particular place by means of the product of the width and mean surface velocity at the place. For brevity, this product may be called the 'transportivity' (surface or floatation capacity) of the river at the given place.
>
> "The transportivity of a river, then, furnishes a test of the probability of a jam or congestion of ice at any place. If it be found, for example, that the transportivity of a stream, relative to the number of square feet of floatage per second to be discharged, is great at one point and small at another a short distance below, it would appear likely that a jam might form at some intermediate place."
>
> "It is evident that water must flow from the main stream to the divergent canal, if there is any draft by consumers along the canal. This will cause a greater or less tendency for all parts of the water in the main channel and diversion channels to flow toward the canal...."
>
> "The transportivity of the intake may now be further reduced by dredging, or otherwise excavating, several channels in a transverse, or oblique, direction across the main stream and leading toward, to, or even into, the intake of the canal. As the channels must be separated by ridges, or other elevations between them, the transportivity of the main stream will not be altered materially if the crests of the ridges are left at the original surface of the bed of the stream."
>
> "The water in the main current, however, is flowing rapidly down the main channel because of the restricted cross-section in that direction, and the water in the transverse diversion channels is not, as it can have no component motion of any consequence at right angles to the direction of the adjacent ridges. The water in the transverse oblique channels, between the ridges and below their crests, can flow with facility only in the direction of, or toward, the intake of the divergent canal, which it does.
>
> "Not so with the water at or near the surface of the main stream at places which are not below the crests of the ridges....

"If the widths of the main stream and intake, the elevations of the crests of the ridges, the depths of the transverse channels, and the geographical configuration of earth and water in the vicinity of the intake have received proper attention with a view to design alteration, construction, and operation, the surface currents of the main stream will not be impelled toward the intake sufficiently to cause any of the water at the surface to move into the intake and down the canal while it is at the surface....

"With sufficient intelligent application of the theory, the surface transportivity of the intake can actually be made negative, so that the surface of the water will flow outwardly there from into the main stream, the canal receiving a sufficient supply of water from the subsurface or lower portions of the main stream to take care of the combined requirements of the canal and negative currents. "

Using a model study he continues to describe the use of jettys, channels, and wings to reduce the transportivity of the canal.

In discussing Groat's paper, Leighton (1918) states one of the primary disadvantages to dredging.

"The natural question that will occur to many readers is 'What will happen to these transverse channels in the bottom of the main stream in the case of rivers that transport debris? Will they not be filled and their effectiveness thereby be eliminated?'

"The foregoing question is very practical. The majority of streams in the United States carry more or less debris. Even in the regions of clear streams, like Northern New England and the far Northwest, a large aggregate quantity of material is rolled along on the bottom of stream channels. This material, being too coarse or too heavy to enter into suspension, is precisely the type that might be expected to lodge in these transverse channels and gradually fill them up. It is true that there might be some cases in which the lateral velocity generated in these transverse channels would keep the channels clear, but in such event Mr. Groat's device would become an efficient instrument for the diversion of large quantities of gravel, etc., into the diversion canal, which gravel, under normal conditions, would continue its course down stream. Thus, the canal operator would have to determine whether freedom from ice troubles for a few days in the year would be preferable to an all-the-year-round deposition of gravel and other material in his canal."

Groat (1918) answers: "The best answer to this is that the writer has already constructed several ice diversion channels, and there is no indication of their filling for many years, if ever. If they do partly fill, they can be dredged out at very little expense."

Parker (1918) feels that conditions on smaller streams might not be similar to those studied by Groat.

> "Under conditions of ice flowing in such large rivers, and with only moderate velocity, the sub-diversion channels described may produce very good results; but, in smaller streams, of heavy fall, such as are usually found in mountainous districts, it is not so evident that the method present would produce the results sought. In mountain streams it is usually necessary to build a diversion dam at each intake. Sometimes such dams may be permanent, and in other cases movable dams are necessary in order to pass the annual spring floods. In the case of a permanent dam, the basin back of it always fills up with silt, sand, and sometimes heavier drift materials, so that in time there is only a limited space of any considerable depth at the intake. Movable dams are erected only at low-water stages, and, when removed to pass the spring floods, the current sweeps the deposits accumulated in the basin cleanly away. Thus the action resulting from the use of either form of dam would evidently preclude the use of sub-diversion channels."

The pressure of ice on bridge piers is discussed by Buznikov, (1933). Means of preventing ice jam damage to pile trestles are outlined by Dalstrom, Helmig and Byrd (1933). V-shaped fender piles are recommended. Ice pressure on sloped ice aprons of bridge piers is analyzed by Zylev (1950).

Channel modification

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CONCLUSIONS

Published information on many aspects of river ice jams is lacking. This is particularly apparent in the area pertaining to the mechanism of formation, growth and decay of ice jams. As a result, techniques of prevention and removal are often inadequate.

Collection of accurate and pertinent data on the mechanism of ice jams is often hazardous. In addition, the time and spatial variability of ice jams presents a problem. These two factors probably account for the success of certain prevention or removal methods on one ice jam and the failure of the methods on another. It is noted that, in almost every method of prevention or removal, positive results are reported by some investigators and negative results by others.

This summary of published investigations can provide a basis for future research. Duplication of effort can be avoided and future projects directed toward critical aspects needing immediate attention.

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13. ABSTRACT

Manuscripts from all areas of the world pertaining to river ice jam characteristics and effects, and methods of prevention or removal have been collected and summarized. Foreign language manuscripts account for a significant portion of the items and were translated as required. The result provides a survey of current and historical information on river ice jams which can provide a basis for future investigations or operations.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
river ice jams						
ice jam formation, growth, decay						
regional ice jam characteristics						
ice jam effects						
forecasting ice jams						
ice breaking						
dusting						
thermal regime modification						
surface and aerial explosives						
ice retention and diversion structures						
surging						
channel modification						